Toward the Development of an
Ocean Observing System
for
Climate Study and Prediction

OOSDP Background Report Number 1

The Role of Models in an Ocean Observing System

Prepared by

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for the

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Joint CCCO-JSC
Ocean Observing System Development Panel

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The Role of Models in an Ocean Observing System

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FOREWORD

Much has been said and written, using sound scientific reasons, about instrumenting the ocean to monitor it systematically. The first major attempt to provide long-term, systematic, real- or near-real-time observations for predictions over a large-scale region was initiated by the Tropical Ocean Global Atmosphere Research Programme and its forerunners in the equatorial Pacific to research the El Niño-Southern Oscillation. The amount of timely ocean observations is being increased by the on-going World Ocean Circulation Experiment and proposed Global Energy and Water Cycle Experiment, initiatives of the World Climate Research Programme, as well as the Joint Global Ocean Flux Study and other components of the International Geosphere-Biosphere Programme.

Although these research programs have limited 10-year lifetimes, they will leave a knowledge base on which to build a permanent ocean observing system. Building such a system is now an accepted international goal, and measurements associated with climate observations are given high priority. It generally is recognized that all marine activities stand to benefit from a comprehensive multi-purpose ocean observing system.

With the need for systematic global observations in mind, the Committee on Climate Changes and the Ocean (CCCO) of SCOR-IOC (Scientific Committee on Oceanic Research – Intergovernmental Oceanographic Commission) and the Joint Scientific Committee (JSC) of ICSU-WMO (International Council of Scientific Unions – World Meteorological Organization) jointly established the Ocean Observing System Development Panel (OOSDP). The OOSDP is charged with formulating the conceptual design of a long-term systematic observing system to monitor, describe, and understand the physical and biogeochemical properties that determine ocean circulation and the effects of the ocean on seasonal to decadal climate changes and to provide the observations needed for climate prediction.

Fundamentally, the ocean observing system must track in a timely manner: the fluxes of heat, fresh water, and carbon between ocean and atmosphere; such fluxes within the ocean; and the storage of these quantities within the ocean. Even with the application of new technology, it seems unlikely that any affordable system of observations alone will accomplish this task adequately. Models with appropriate constraints will be necessary to tie sparse observations together and produce products with the required time and space scales. The observing system must provide those measurements to develop, verify, and initiate the necessary models.

The OOSDP, a small group of scientists from five countries, spent its initial meetings dealing with the organization of the work, the approach to be followed, and the preparation of draft background papers to help identify system design considerations. The OOSDP plans that these informal background papers will identify: (1) the elements of the Ocean Observing System (OOS) as defined by scientific requirements (as per its charge); (2) existing capabilities available to meet these needs; and (3) new types of systems that should be encouraged in order to meet these needs more economically and efficiently in the future. These background reports are being distributed widely for information and comment.

The paper presented here is one of these background reports. It is being distributed for information and for review. Your comments, criticisms and suggestions may be sent either to Dr. Neville Smith (Bureau of Meteorology Research Centre, Box 1289K, Melbourne, Victoria 3001, Australia) or to the OOSDP chairman, Dr. Worth D. Nowlin, Jr. (Department of Oceanography, Texas A&M University, College Station, TX 77843-3146, USA).

Clearly the ultimate success of implementing an ocean observing system hinges on broad acceptance of its plan by the ocean science community and by the national agencies and intergovernmental organizations that will have to implement it. That, in turn, depends on broad informed participation. The Panel members accepted their appointments expecting to draw on the expertise of many other scientists, and from the concerned national and international groups, to produce a credible product by the December 1994 target date. The effort will certainly fail if it is perceived to be the parochial product of only the small OOSDP core group. Accordingly, addressees are earnestly requested to give this document more than the ordinary attention they might otherwise give to unscheduled intrusions that place demands on their time. The task is difficult - the outcome is important - the feedback is essential.

Joint JSC-CCCO
Ocean Observing System Development Panel

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Preface

The OOSDP was established to formulate the conceptual design of an observing system for the oceans and climate. The goals of the OOS include monitoring, understanding, simulating, and perhaps predicting, the physical, chemical and biological changes in the ocean climate system. An important element of this will undoubtedly be the effective implementation of a range of ocean models to help in the interpretation and assimilation of the data. For the foreseeable future this will not be accomplished by any single "super" global climate model, but by a suite of different models each suited to a particular aspect of the ocean climate system.

The present background paper on the role of ocean modelling in the planned OOS was suggested as a way of fostering discussion among the ocean (and general climate) scientific community so that the Panel could be fully cognizant of the range in opinions. The theme of my approach is the successful marriage of the observing and modelling parts of the system for their mutual benefit, so that there is no effective distinction or demarcation between modellers and observers. I have endeavoured, within the limitations of my knowledge, to give an up-to-date account of modelling activity which is likely to impact on the design and implementation of an operational system. It is likely that too little attention has been paid in some areas, while in others my personal interests may have led to undue emphasis. Some aspects, such as the oceanic carbon cycle and biogeochemical fluxes, will be discussed in more detail in forthcoming OOSDP reports. I should stress that this paper is a <u>review</u> of modelling and <u>is not</u> intended as an endorsement or recommendation for any specific model or modelling strategy. I hope that any ensuing discussion between the Panel and interested parties in the scientific community will help redress any imbalances or misconceptions within the paper, and lead to a coherent treatment of modelling in the final OOSDP report.

To ensure as wider coverage as possible, this paper will also be submitted to a scientific journal and will be subject to the normal scientific review process. Any comments received as a result of this initial limited distribution will be considered in the preparation of the final manuscript.

This paper has benefited from the many vigorous discussions within the OOSDP, and from the careful reading by members of the Panel. In particular, Worth Nowlin, Peter Niiler, Liliane Merlivat, George Needler and Art Alexiou made many helpful suggestions, while Alain Vézina made a significant contribution to the bilogical discussion. I thank all members of the Panel for their interest and assistance. Encouragement and insightful comment was also forthcoming from several colleagues and guests of the Panel. In particular I would like to thank Bill Budd, Peter McIntosh, Scott Power, Carl Wunsch, Kirk Bryan, Dale Hess, Richard Kleeman, John Wilkin and Andrew Moore for their help along the way. The comments of Ping Chang of TAMU on an initial draft of this document were greatly appreciated. I am grateful for the support of the Bureau of Meteorology Research Centre in allowing me sufficient time to complete this review.

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Summary

An overview of ocean modelling in the context of formulation of the conceptual design of a long-term systematic ocean observing system is presented with the aim of providing the necessary background for a discussion of the role of models within that system. The modelling is not considered as separate and distinct from the observing component but rather as an integral part of a complete system in which observing and modelling elements operate in concert. For practical reasons the discussion is limited to modelling of the surface fields, the seasonal mixed layer, the tropical oceans, the thermocline waters, and the deep water. Neither the coastal zone nor the biological and chemical components are discussed in any detail.

For each of these components the focus is on the degree of interfacing between the models and observations. In the first instance models and observations can be treated as independent elements, with the interfacing being a subsequent validation/verification step. The models in this category are simulation or interpretation tools. A more satisfactory arrangement is to configure the model so that data are assimilated in the process of model solution, and the solution used as an initial condition for a prediction of future conditions. In this category the models and data operate jointly. The final level of sophistication allows the model to feed back information into the observing system, either to assist in its design or to control the operation of the observing system. In this case the emphasis turns to network design and quality control of data.

Models of the ocean surface fields and of the exchanges of momentum, heat, nutrients, gases, moisture and light across the interface are central to defining the role of the oceans in climate change. The best estimates of surface fluxes are probably from numerical weather prediction (NWP) centres where both surface and atmospheric data are combined with a model to form a joint estimate. Nevertheless, traditional bulk aerodynamic methods remain useful, particularly for estimates of the climatology. Ocean models are playing an increasingly important role in flux estimation, first as a validation tool for NWP estimates, and second as an independent source for estimating net heat and moisture flux at climatological scales. Estimates of the surface fields are usually obtained without any skilful input from oceanic models, although this is beginning to change as "operational" oceanographic centres come into being. Sea surface temperature analyses are most developed, but lack of data essentially precludes anything other than climatological estimates of fields such as surface current or surface salinity. Modelling and analysis of ice conditions is also discussed.

Developments in modelling the surface mixed layer are closely linked to determinations of the surface fields. The various approaches to mixed layer modelling are first reviewed, including research with biological-physical models, and their relevance to the ocean observing system discussed. The role of mixed layer physics in the process of combining observations and model estimates is unclear. Experience in NWP is used as a guide to possible problems in ocean mixed layer data assimilation. Some important areas for research and development are listed.

The tropical oceans offer unique opportunities for the development of operational ocean prediction systems. The Tropical Ocean Global Atmosphere experiment has laid the groundwork for much of this development and has been active in ocean modelling and observing system design. The development of tropical ocean models is discussed,

principally with a view toward ocean-only assimilation and prediction systems, but also with regard to their role in coupled ocean-atmosphere systems. Several institutions have studied the feasibility of operating real-time ocean analysis and prediction systems and, in general, reported positive results. While further research and development is required in both the modelling and observing components, the indications are that the observation and model information can be combined usefully both for the purpose of analysis and forecasting, and for furthering our understanding of the tropical ocean system. Methods of network design and objective quality control have advanced considerably in this area.

Mesoscale eddies, gyres, ventilation, and subduction are all part of the thermocline problem. Knowledge of these processes has advanced considerably due to the skilful application of simplified models whereby compromises in the configuration or physics are made in order to make the solution of the problem tractable. The contribution of low vertical resolution models, quasi-geostrophic models, balanced models, and isopycnic models is discussed in relation to simulation of mesoscale eddies and subduction. The promise of "synoptic" global sea level coverage by satellites has prompted considerable research into the assimilation of data into such models, particularly eddy-resolving models. It is not yet clear whether there will be sufficient data to constrain the eddy field, or whether the smaller large-scale signal can be extracted from the mesoscale noise. Attempts to implement ocean "weather" analysis and forecast systems and the role of observing system simulation experiments are discussed.

Models of the deep ocean are central to the considerations of both the ocean observing system and the global climate observing system. Early developments in ocean general circulation modelling are reviewed and current developments, particularly within the World Ocean Circulation Experiment, are discussed. The discussion of the ocean-only models is centred around recent attempts at eddy resolving simulations for the North Atlantic and the Southern Ocean, and an attempt at a global eddy-resolving model. A model for water mass formation is also discussed in view of the important role such processes play in the global physical, chemical and biological cycles. Ocean models for global coupled ocean-atmosphere climate studies are also briefly reviewed, as are models for following the three-dimensional transport and storage of tracers and models for physical-biological interactions. Inverse methods are used to interface models and data from the deep ocean. The beta-spiral and inverse box models are discussed and their application in the determination of ocean circulation briefly reviewed. Both the inverse and prognostic approaches to the determination of the deep ocean circulation are extremely demanding of resources. In view of the limitations on both the observing and modelling components it is critical that the information derived from each be maximised. The results from the global research programs currently underway, and from planned experiments, will be critical in learning the best way to use the limited resources available for monitoring and understanding the deep ocean.

1. Introduction

It is clear that understanding of the ocean will not come from either observations or modelling alone, but will depend on our ability to skilfully marry the two approaches. From the point of view of modelling within an ocean observing system (OOS), the development and application of ideal "fluid" models independently of the guidance and constraints provided by oceanic observations is likely to be of limited direct use. Such models, while theoretically interesting and satisfying, belong in the realm of theoretical fluid dynamics and are of little functional use in the design of an ocean observing system. This somewhat narrow view of oceanic modelling immediately restricts and focuses the scope of this review and draws the measurement and modelling components closer together. In some cases the model development simply cannot proceed without guidance from observations. For example, it is not clear at this point whether the deep hydrographic measurements of the World Ocean Circulation Experiment (WOCE) are representative of the equilibrium state of the ocean, in which case equilibrium models of the ocean are appropriate, or whether they are simply samples from a slowly evolving climate system thus requiring an altogether different and more complex modelling strategy.

The case against an isolationist approach is equally clear from the observers point of view. No matter how successful an OOS is at garnering resources it will never be sufficiently dense in either space or time to provide an adequate description of the three-dimensional, evolving ocean system. Some observing systems (e.g. satellites) might provide a quasi-synoptic picture at one level of the ocean, perhaps even at the requisite horizontal and temporal resolution, but we cannot expect to ever have a comprehensive four-dimensional sampling system, nor be able to return to the past and gather the long time series that are necessary for constructing a complete understanding of the oceans. Models can at least provide some assistance in this regard, enabling information to be interpolated and extrapolated in space and time, as well as guiding scant observing resources toward locations and processes that are critical to the observing system.

This paper aims to give an overview of ocean modelling in the context of the design and development of a global OOS, concentrating on the temporal and spatial scales that are of most relevance to climate change. It has no pretensions to being all-encompassing even within the narrow scope outlined above, and through necessity must gloss over much of the interesting detail of individual models. The intention is to provide the reader who is interested in the design and development of an OOS with a background review as a basis for further discussion of the role of models within that system. In order to address the wide variety of models and model applications in an orderly manner the following discussion has been stratified first by system components. This division is functional rather than unique, and the system components are far from being independent, yet it does provide a convenient demarcation for the present purposes. The components are:

- *Surface* - models targeted specifically at the ocean surface or at the fluxes through the surface. Also ocean-ice modelling.
- *Seasonal boundary/mixed layer* - the physics of the upper ocean, principally one-dimensional mixed layer models. Includes some discussion of physical-biological models.
- *Tropical waters* - a convenient component to distinguish models for the mixed layer and thermocline from those developed specifically for seasonal and interannual variability in the tropics.
- *The thermocline problem* - models of the subtropical gyres, mesoscale eddies and thermocline ventilation and subduction.
- *Deep (cold) water sphere* - the realm of OGCMs and inverse models, but with connections to models in previous categories and to global coupled models. Includes deep convection, estimates of transport of energy, water, nutrients, CO_2, etc.

We will avoid a detailed discussion of modelling for the coastal zone which is covered elsewhere (e.g., the Coastal Ocean Prediction System, 1990). Physical-biological modelling and modelling of the ocean carbon cycle will only be discussed briefly here. A separate discussion paper will deal with these issues in detail (Merlivat and Vézina, 1992). Each of the above components are developed in terms of the roles models will play in the development of an ocean observing system. These roles can be classified according to the interface established between the observing and modelling systems. Again this demarcation is used for organisational convenience.

(1) Interpretation and simulation.

Analysis methods (or data interpretation) and model simulations treat the observing and modelling components as *individual systems*, with the interface being provided by a validation/verification step (the data analysis is used to verify the model or, on some occasions, the reverse).

(2) Assimilation and prediction.

The next level of sophistication is to allow the observations and model to *jointly* determine the solution. Such techniques have many names but we will use "inverse modelling" to describe the class of models which seek equilibrium solutions, and assimilation and prediction to describe the evolutionary system, whereby a solution is mapped out in time by combining model and observed information. In the latter case the concept of numerical ocean prediction (NOP) systems, along lines similar to numerical weather prediction (NWP), will be the theme.

(3) Network design and quality control.

Since we are concerned with the conceptual design of an OOS a further important role for models is their ability to *feed information back to observing systems*, aiding in the design of the observing network, and helping to monitor the quality of data. In the former case observing system experiments (OSEs), where actual systems are varied, and observing system simulation experiments (OSSEs), where synthetic systems are tested, have important roles. However the technical complexity of such experiments, and the sometimes limited reward for effort, suggests scientific intuition and experience could be effective alternate strategies. Models play a crucial part in the quality control of atmospheric data in NWP and it is to be expected that ocean models will play a similar, perhaps even more important, part in the OOS.

(4) Developments.

Finally, for each of the components, we attempt to identify aspects whose development will be important for OOS. At this stage, and without the benefit of results from WOCE, the Joint Global Ocean Flux Study (JGOFS), the Global Energy and Water Cycle Experiment (GEWEX) and the last half of the Tropical Ocean Global Atmosphere (TOGA) program, this part will involve some conjecture and is written in the expectation that substantial modifications will be required as the planning for the OOS (by the Ocean Observing System Development Panel, OOSDP) proceeds.

2. The ocean surface and air-sea exchanges

While information from all the ocean is needed to form a complete description of the ocean circulation, it is perhaps information from the interface with the atmosphere which will be most important in defining the ocean's role in climate change. Sea surface temperaturte (SST) has long been regarded as a crucial signature of the ocean's function in climate. For the OOS our list of variables is broader and includes sea surface salinity (SSS), sea surface state (waves), ocean colour, surface current, carbon dioxide, transparency, and so on. This section examines models which are specifically directed at the surface fields and, since we are at the surface, also examines models which provide information on the flux through the ocean surface (wind stress, heat, moisture, CO_2, light, dust, biogeochemical fluxes, etc.). For the most part we will be concentrating on systems where the role of the deeper ocean is trivialised, as in NWP and wave forecasting systems, so that surface information is garnered almost independently of the ocean sub-surface structure.

2.1.1 Surface flux simulations

Global air-sea flux estimates are vital for the development and understanding of ocean circulation, particularly in view of their key role in uncoupled ocean model applications. The first air-sea flux climatologies were developed from one-dimensional parameterizations of the planetary boundary layer (the bulk aerodynamic method) in which observations of SST, air temperature, humidity and near-surface wind speed were used to estimate the transports of momentum and heat through the ocean surface (e.g. Hellerman, 1967; Esbensen and Kushnir, 1981; Weare et al., 1981; Hellerman and Rosenstein, 1983; see also the discussions in Taylor, 1989). Similar techniques have been used in more recent times to provide improved estimates of the global ocean flux and surface drag coefficient (Oberhuber, 1988; Trenberth et al., 1989) and to provide regular analyses of surface stress over the tropical oceans (e.g., the Florida State University wind stress products, Legler and O'Brien, 1984). Oberhuber (1988) is a good example of climatological flux estimation using modern data bases such as the Comprehensive Ocean-Atmosphere Data Set (COADS). Such estimates are however restricted by the limited data base (usually surface *in situ* data), poor data coverage, and uncertainties in the planetary boundary layer parameterizations including model-to-model variations (Weare, 1989).

In the near term it is reasonable to expect that the best estimates of air-sea fluxes of momentum, heat and water will be derived from operational NWP schemes that combine *in situ* and satellite data. While such schemes are also subject to uncertainties with respect to the planetary boundary layer parameterizations (perhaps even more so), and errors associated with the imperfect physics of the models, they are able to incorporate a vast array of information in forming the air-sea flux estimate, including data away from the surface, non-*in situ* data and information derived from the interpolative and extrapolative skill of the prediction model. These products are undergoing continual assessment (Arpe et al., 1988; Taylor, 1989; Simonot and Le Treut, 1987; Burridge and Gilchrist, 1989; Barnier and Simonot, 1990; Arpe, 1991) and are likely to benefit from specialist attention during WOCE (e.g. Jochens, 1990) and TOGA (e.g. the TOGA Program on Seasonal-to-Interannual Prediction, UCAR, 1991), and from efforts to expand the domain of influence of NWP to include ocean surface processes explicitly within the data assimilation cycle (e.g. the Global Data Assimilation Program (GDAP) for Air-Sea Fluxes, WCRP, 1989a). These programs aim to add an important dimension to the determination of air-sea fluxes, namely information at the time and space scales which are important for the ocean as distinct from scales important for short-range forecasts. For example, sophisticated wave models are now providing skilful evaluation and validation of NWP surface stress products in near-real-time.

Other methods are available for estimating the surface fluxes relevant to climate studies. Atmospheric General Circulation Models (AGCMs) also diagnose surface heat flux, but without the additional knowledge provided by ingestion of atmospheric data (but with some knowledge of SST). Lambert and Boer (1988, 1989) have undertaken a comparison of such products, the quality of which are, in general, directly determined by the quality of the model. Randall et al. (1991) and Gutowski et al. (1991) discussed the surface energy fluxes in AGCMs and the implications for simulating global and regional climate change. There are clearly significant differences from model to model. The climate drift problem in coupled models is a direct consequence of imperfections in the AGCM and Ocean General Circulation

Model (OGCM) components (Sausen et al., 1988; McCreary and Anderson, 1991). A further possibility for estimating fluxes is to derive surface flux as a diagnostic of a NOP or OGCM simulations. Initial tests (e.g. Gaspar et al., 1990; Leetmaa, 1990; Smith et al., 1992) have been promising and suggest that as such systems mature they will provide valuable independent estimates of net surface heat and, perhaps, moisture flux.

Estimation of the radiative sea surface budget is of interest to heat budget studies and biological models. Morcrette (1989) discusses the radiative balance in the ECMWF NWP scheme, which we can assume is typical of the highly complex operational NWP products. While estimations at the top of the atmosphere are good (Morcrette and Fouquart, 1988), the surface fluxes are generally larger than climatological estimates (e.g. Esbensen and Kushnir, 1981). Simonot and Le Treut (1987) identified a systematic difference in the (old) ECMWF scheme of around 20 W/m^2, with largest errors in the tropics. While the global annual mean and local distributions of surface heat flux are better in the new scheme there remains a systematic error (20 W/m^2) in the shortwave radiative flux (Barnier and Simonot, 1990). They suggested this bias may be related to cloud cover and cloud optical properties. Gutowski et al. (1991) found that AGCMs (for coupled studies) often differed in their downward longwave and absorbed shortwave estimations, the discrepancies being larger than the climate change signals being sought (they concluded these discrepancies would not adversely affect the results). Yu et al. (1991) compared the spatial and temporal variability of observed and simulated radiance fields and concluded that, at the resolution of the GCM, there was reasonable accord, although the model tended to give slightly smaller results. For climate studies in general, and for coupled models in particular, such considerations are assuming increasing importance.

The above discussion is concerned principally with the estimation of fluxes of momentum, heat and moisture, but for the OOS fluxes of CO_2, dust, nutrients, chemical exchange, and a range of species are also important. However at this time models do not have a prominent role in these estimations.

2.1.2 Surface field simulations

For the surface fields themselves, analysis and interpretation of data has usually been carried out with minimal interfacing to models, although this is now beginning to change. The analysis of SST, for example, has traditionally been performed without recourse to thermodynamic models of the ocean, instead relying on simpler concepts of the temporal and spatial variability of SST to aid in merging, interpolation and extrapolation of information (e.g. Reynolds, 1988; Levitus, 1982). The mapping of other fields, such as SSS (Levitus, 1986; Delcroix and Henin, 1989) or precipitation is primitive since what little is known suggests small scales of spatial and temporal variability.

Most studies relevant to the simulation of surface fields, in particular SST, have broader aims than just simply simulating the variability of the surface field itself, and thus fit more neatly into the discussion of seasonal boundary layers, the tropical ocean or deep water models. It is fair to say that, given good quality boundary conditions (surface forcing), mixed layer models are capable of reproducing the diurnal and seasonal variability of SST, SSS, phytoplankton distribution, etc. (Martin, 1985; Miyakoda and Rosati, 1984; Woods, 1985; Seager et al., 1988; Seager, 1989; Woods, 1988; Clancy et al., 1990). These issues are developed further in the following section.

Finally mention should be made of models for sea surface state and, in particular for ocean waves. There are a wide variety of models in use. The third-generation wave prediction model (WAM) of the WAM Development and Implementation Group (The WAMDI Group, 1988) is widely used and documented and, for the purposes of the present discussion, can be taken as representative of the state-of-the-art in this area. WAM computes the spectral density as a function of frequency and direction over a global (or regional) grid, with the wind and pressure fields providing the external forcing. WAM can be used at varying degrees of complexity depending, among other things, on the resolution and complexity of the non-linear interactions which are retained in the model. Ultimately the success of the model is dependent on the verisimilitude of the forcing. At this time observations, for example from wave-rider buoys or from remote-sensing devices, are mainly used as independent verification points of the model simulation. However this situation is likely to change in the near future as altimeter and SAR data become available from ERS-1 and other satellite missions, some of it in real-time. The WAM model has been actively used in the calibration and validation of both the altimeter and scatterometer of the ERS-1 mission through real-time trials in parallel with the ECMWF analysis and forecast system.

2.1.3 Ocean-ice interactions

For climate scales it is clearly important to take account of ocean-ice-atmosphere interactions at high latitudes. For the OOS we are particularly concerned with the effects on energy and water exchange. Sea ice effectively insulates the ocean from incoming radiation (increased albedo), and moderates the exchange of heat between the ocean and atmosphere. This exchange is felt most strongly in the oceanic mixed layer, but it is also important for the rates of formation of deep and bottom water masses (e.g. Antarctic Bottom Water). It is not appropriate for this document to detail the mechanics of ice growth, movement, and decay, nor to delve into the complex models that are now available for modelling the cryosphere. The WCRP Working Group on Sea Ice and Climate (e.g. WCRP, 1988a,1989b) and the associated Numerical Experimentation Group (e.g. WCRP, 1989c) discuss these issues, particularly within the context of coupled ice-ocean-atmosphere modelling. This section will instead simply summarise the state-of-the-art for ice modelling, and highlight issues relevant to OOS.

Washington and Parkinson (1986) gave a full account of current ice model configurations. Sea ice models usually consist of four parts (Lemke, 1991):

(a) A surface energy balance which takes account of incoming and outgoing radiation, atmospheric heating, and upward conduction of heat through the ice to calculate the surface temperature.

(b) An ice thermodynamic model for determining the rate of heat conduction through the ice.

(c) A momentum balance. Atmospheric and ocean stresses, Coriolis forcing, sea surface tilt and internal ice strain, are used to predict the ice velocity.

(d) A water budget which takes account of surface accumulation, internal movement, and melting to determine the spatial variability of ice thickness and concentration.

Hibler (1979), Owens and Lemke (1990) and Parkinson and Washington (1979) are typical of ice models being used in coupled studies.

Sophisticated sea ice models have so far only been applied to limited regions (Arctic Ocean, Weddell Sea). Global models usually adopt a much simpler thermodynamic configuration (e.g. Washington and Meehl, 1986), and retain only very simple advection of sea ice. Experiments with ice models coupled to mixed layer models show that the vertical oceanic heat flux can be significant at the ice edge (Stössel et al., 1990). Lemke et al. (1990) have shown that the supply of heat from the ocean to the ice is not constant, but is spatially and temporally variant, being largest in winter and in ice-divergent areas (large freezing rates and enhanced convection). Hibler and Bryan (1987) and Willmott and Mysak (1989) showed that advection of heat by the ocean currents toward the ice pack is important for simulating the location of the ice edge. These results clearly indicate ocean-ice coupling is important for climate studies. The currently used purely thermodynamic configurations (for global studies) are probably extra-sensitive to changes in the boundary conditions; dynamic sea ice models have reduced sensitivity because of thermodynamic-dynamic interactions which provide a stabilising effect (WCRP, 1988a). Both Lemke (1991) and WCRP (1988a) included tables of currently used ice model configurations in climate studies.

Lemke (1991) discussed facets of (Arctic) ice modelling research which needed further effort. The role of ice rheology in sea ice - ocean interactions must be investigated and validated against observations of ice drift and ice concentration / distribution. The thermodynamics of sea ice are known to be sensitive to the surface energy balance, particularly the surface albedo specification (Meehl and Washington, 1990). In turn, atmospheric models are known to be sensitive to the relative distribution of sea-ice and open water (Budd et al., 1990). Within the ice the rate of heat conduction, and its dependence on inhomogeneities in the ice coverage (e.g. brine pockets and surface melt water), should be investigated. This problem is linked to the ocean mixed layer processes which transport heat and water both vertically and horizontally (e.g. Fichefet and Gaspar, 1989; Mellor and Kantha, 1989). For coupled ice - ocean general circulation model studies the resolution of the ocean model near the ice becomes an important factor. Uncertainties in the surface forcing (see Section 2.1.1) also hamper the development of ice models. The most consistent forcing fields are from NWP and these have been successfully used to drive Southern Ocean sea ice-mixed layer ocean models (Stössel et al., 1990).

Recent developments in the understanding of ice dynamics and thermodynamics have been greatly enhanced by satellite data (passive microwave for ice concentration, Synthetic Aperture Radar (SAR) for concentration and velocity). The total data requirement for validation of sea-ice models (e.g. see Table II of WCRP, 1988a) has many elements in common with OOS requirements. In particular the role of drifting buoys and upward-looking sonar on oceanographic moorings give information important for both. The use of NWP and AGCM products is also a common need.

2.2 Assimilation and prediction at the surface

The marriage of data and models can be seen in their most sophisticated form (for example, in NWP), or in their most primitive form (sea surface field analyses), depending upon which aspect of the surface is under attention. NWP offers great promise for the accurate (in terms of climate) determination of sea surface fluxes of momentum and heat, and perhaps of water. In so far as the accuracy can be established from independent estimates, it would seem that NWP is good at producing surface stress estimates, but less successful in respect of radiative, sensible and latent heat flux estimates (Arpe et al., 1988; Lambert, 1988; Lambert and Boer, 1988; Burridge and Gilchrist, 1989). The confidence in such products is not uniform over the globe, mainly due to the disparate data coverage of the two hemispheres. Arpe (1991) suggested NWP may now be able to deliver accurate estimates of the latent heat flux over the Northern Hemisphere extra-tropical oceans, but was less certain about the Southern Hemisphere and tropical estimates. The accuracy of sea precipitation estimates is uncertain. Arpe (1991) compared ECMWF estimates with both climatology (Jaeger, 1976) and satellite estimates (Janowiak and Arkin, 1991; Arkin and Janowiak, 1991) and, in the zonal mean, obtained respectable agreement. The precipitation estimates are affected by spin-up problems in both the tropics and Southern Hemisphere, so Arpe (1991) suggested using the 0.5-1.5 day forecast mean as a reasonable compromise.

Action at operational centres (e.g. Jochens, 1990; Janowiak et al., 1987) and through programs like the Global Precipitation Climatology Project, the Tropical Rainfall Measurement Mission (TRMM) and GEWEX will no doubt improve this situation. It remains to be seen whether the necessary conditions for accurate determination of surface flux include, first, a more sympathetic treatment and assimilation of marine boundary layer measurements and, second, explicit representation of ocean boundary layer physics rather than its proxy SST. The problem of validating such products will be the subject of a separate discussion paper (Taylor and Weller, in preparation).

For the sea state problem, research is already under way to incorporate wave models such as WAM within the analysis-assimilation-prediction cycle of operational NWP. With the possibility of remotely sensed sea state data becoming available, it is feasible that such data can be used not only to correct the wave model prediction through better initialisation, but also to assist in correcting the surface wind forcing. The GDAP document (WCRP, 1989a) presented a vision which involved a comprehensive data assimilation system capable of gathering information from many different sources and in a variety of forms, with all parts working in concert to produce atmospheric, sea surface flux and sea surface state analyses and predictions.

Of the sea surface variables, only SST is being assimilated and predicted in any skilful way. The Optimal Thermal Interpolation System (OTIS) of the Fleet Numerical Oceanography Centre (FNOC) produces nowcasts of ocean temperature by combining data from various sources with both climatology and model forecasts (Clancy et al., 1986; Clancy et al., 1990). Clancy (1989) and Cummings (1990) discuss plans to interface "ocean feature models" with the thermal analysis scheme so that ocean front and eddy structures can be mapped at both the surface and subsurface levels, even in the absence of subsurface data. The Climate Analysis Centre uses a variety of techniques to produce SST analyses, some of which combine stochastic and/or deterministic model forecasts with *in situ* and AVHRR data (Reynolds, 1988), and others which use a primitive equation equatorial ocean model combined with an optimal interpolation scheme (Reynolds and Leetmaa, 1989). Folland et al. (1991) and Folland et al. (1992) present an evaluation and intercomparison of several operational SST analysis systems. Present indications are that deterministic models are not quantifiably better than stochastic methods (e.g., persistence), but this will no doubt change as the sophistication and resolution of ocean data assimilation systems improve.

A related category of models are employed for predictability problems within the TOGA program. Systems such as Barnett's (1984) statistical prediction scheme for the El Niño - Southern Oscillation (ENSO), or the Cane et al. (1986) dynamical prediction scheme for El Niño are in effect predictions of anomalous SST in the Pacific Ocean. These schemes appear to provide predictive skill at least out to several seasons, and perhaps even to a few years (UCAR, 1991). However the schemes do not assimilate oceanographic data in the normal sense, but use prior analyses of wind and SST as predictors/forcing functions.

There is almost no activity in assimilating or predicting other surface physical, biological and chemical parameters, principally because of lack of data. One of the aims of GDAP was to incorporate remotely sensed surface data (e.g. altimeter, scatterometer, SAR, Coastal Zone Color Scanner (CZCS)) in a comprehensive data analysis and assimilation system.

2.3 Network design and quality control for surface fields

An essential component of NWP is the application of objective quality control techniques to ensure the integrity of ingested data. Major operational centres, such as the ECMWF (Palmer et al., 1990) and NMC (Kalnay et al., 1990; Gandin, 1988), have strong links between the analysis/prediction system and the data collectors. The ECMWF, for example, routinely check the outcome of quality control, feeding information back to measurement platforms where necessary. NMC have developed self-correcting techniques to improve the quality of ingested data. NOP centres, such as those being developed at NMC (Derber et al., 1990), LODYC/ORSTOM (Morliere, 1990), FNOC (Clancy and Pollack, 1983; Phoebus, 1990), BMRC (Smith, 1991a,b), and elsewhere, are incorporating similar feedbacks but these have yet to be fully implemented operationally. None of the existing NWP quality control systems are particularly well attuned to the needs of ocean surface (flux) fields. Indeed in many systems much of the conventional marine-based data is not retained in the analysis system due both to lack of confidence in the data and to problems in the model planetary boundary layer.

There have been few OSE or OSSEs studies specifically directed at the oceanic surface fields. As part of FGGE, many OSSEs and OSEs were performed to gauge the influence of particular systems on NWP (Bourke et al., 1985; Smith, 1989), but none of these took account of the degradation/improvement of air-sea flux estimates as a result of atmospheric observing system changes (one possible assumption might be that improved model forecast skill does imply improved surface fluxes). Such experiments should be done. Leetmaa (1990) was among the first to use oceanographic models actively in the assessment of observing systems, in this case platforms for measuring SST, and was able to quantify the relative accuracy and worth of different measurement platforms.

2.4 Developments

In designing the surface component of OOS we should remember that NWP has played a significant role in the establishment of the existing measurement system, and that these needs may not be commensurate with the requirements of OOS. For example, SST analyses are often smoothed at the scales of meteorology, thus omitting important oceanographic features. There is a need for a more active role for ocean models in the design of measurement systems such as in the NMC example cited above. Such investigations, together with carefully planned OSSE/OSEs, will be required if the OOS is to provide good quality surface fields. For example, it may be possible to use models in the design of a SSS measurement program.

It is likely that ocean modelling of surface fields and fluxes will be more strongly linked to models for the subsurface circulation of physical, chemical, biological and dynamical fields. Upper ocean mixing models play an important role in the simulation and prediction of non-thermodynamical surface fields (Archer, 1990), and continued experimentation and improvement will be important for the OOS. Improvements will come from the merging of separate components which are themselves well understood. In this respect regional analysis and assimilation, say for the coastal regions where the skill of the model, observation density, and quality control can generally be better controlled than in a global system, could play a significant role. We might view the coastal regions as additional buffer zones for fluxes of nutrients, water, etc. into the upper and deep oceans, in much the same way as we view the surface boundary layer.

3. The seasonal mixed layer

The seasonal component of the ocean system is here defined as that portion of the water column which is continually changing on diurnal and seasonal time scales, be it through the action of winds and wintertime overturning as in mid-latitudes, or through the formation and decay of ice at high latitudes[1]. From a modelling perspective we are mainly concerned with the so-called "mixed layer" class of oceanographic models although, as with other components, there is clearly an important function for other models in determining the evolution, structure, and physical, chemical and biological composition of the layer.

The mixed layer provides a buffer zone between the higher frequency scales of atmospheric forcing and the slow, large scale circulation of the thermocline and deep waters of the ocean. This buffering action is probably most critical for the chemical and biological components as, for example, in the regulation of the pCO_2 and pH of the oceans. Microscopic plants and animals (the plankton) consume some of the CO_2 dissolved in the mixed layer and sequester the carbon into the thermocline and deep waters, away from the immediate influence of high frequency processes at the atmosphere-ocean interface (Cubasch and Cess, 1990). The seasonal layer water gradually leaks into the permanent thermocline, thus determining the stratification and biogeochemical balance of the interior of the ocean (Pedlosky, 1990). These processes must be accurately observed and modelled if we are to understand the larger role of oceans in climate change.

The need to isolate the seasonal mixed layer as a distinct component in the context of the modelling discussion comes more from the recognition that mixed layer

[1] Deep convection will be considered in section 6

models are distinctive entities in the global scheme of ocean modelling. The need for parameterization of horizontal mixing by eddies can reasonably be expected to lessen as eddy resolving models are implemented, but the representation of the dominant processes in vertical mixing cannot be improved by simply adopting finer vertical resolution. Judging from the experiences of NWP where the parameterizations for the planetary boundary layer and convection have proved critical in the assimilation and quality control of data, we might expect model developments for the oceanic boundary layer to be similarly crucial for the implementation of simulation, assimilation and prediction schemes for climate scales in oceanography.

3.1.1 Models for Interpretation and Simulation of mixed layer physics

By far the majority of studies of the seasonal boundary layer have been concerned with the interpretation of data, leading to improvements in vertical parameterization, and with the simulation of the vertical structure of the boundary layer (particularly mixed layer depth). Niiler and Kraus (1977) gave a good account of the fundamentals behind one-dimensional models of the upper ocean, while current research in the parameterization of small-scale processes is discussed in Müller and Henderson (1989). The "Coastal Ocean Prediction System" workshop (COPS, 1990) also contained several papers relevant to the issues discussed here. Archer (1990) reviewed the physical, chemical, and biological processes which are relevant to the modelling of ocean boundary layer variability, paying particular attention to the modelling of surface pCO_2 and pH in the oceans. The discussion can be broken into three families of mixed layer models according to the conceptual approach, but it should be remembered that there is considerable overlap and commonality between these approaches.

Integral or bulk models (Kraus and Turner, 1967) are an expression of the idea that the surface boundary layer is well mixed, so that the variables within this layer do not vary vertically. The mixed layer depth, and variable values within the mixed layer, are constrained by the fluxes of turbulent kinetic energy (TKE) and buoyancy through the surface, and by entrainment (detrainment) of water from (on to) the seasonal thermocline. The credentials of the bulk approach have been established by a range of studies (Stevenson, 1979; Niiler and Kraus, 1977; Garwood, 1977; Kim, 1976; Miyakoda and Rosati, 1984; Martin, 1985; Gaspar, 1988). Seager et al. (1988)

and Seager (1989) described an SST prediction scheme based in essence on bulk turbulent closure theory. With a reasonably simple heat flux, and optimally tuned parameterizations (Blumenthal and Cane, 1989) they are successful in hindcasting SST, particularly in the tropical oceans.

A second class of models relies on the TKE generated by internal shear of the mean flow to drive vertical mixing. The mixing is parameterized in terms of the Richardson number, either in its bulk form for models based in the mixed layer concept (Pollard et al., 1973), or the gradient form for (local mixing) models with continuously varying shear (e.g. Pacanowski and Philander, 1981). Some more recent adaptions rely on a combination of both (e.g. Price et al., 1986). The fact that these shear instability models develop the mixing parameterization in terms of the mean flow, and hence are cognisant of large-scale effects like the Coriolis effect, is the major conceptual distinction between the bulk and shear instability approaches. This can lead to improvements in the simulation of mixed layer variability since the inclusion of inertial effects provides a natural limit to the mixing and to mixed layer velocity.

The third family are the second moment closure (SMC) models whose foundations lie in turbulence theory. The governing equations are formally derived by expanding the momentum and tracer equations (heat, salt, etc.) in terms of their mean and fluctuating (turbulent) components (Mellor and Yamada, 1982, Mellor, 1989a). Higher order expansions, and various closure hypotheses, are used to derive closed expressions for the Reynold's stress and eddy diffusion terms. The fact that the derivations are based on general turbulence theory, and empirical constants derived from laboratory results, means SMC models are in theory not site specific, but can be applied in a variety of different situations. Mellor and Yamada (1974) and Mellor (1985) present a hierarchy of models, ranging from the level 4 closure (anisotropic turbulence) down to the locally dissipative level 2 model (shear and buoyancy generated TKE is assumed to be dissipated locally). The SMC models have been applied in a variety of oceanic situations, finding particular favour in simulations of bottom boundary layer behaviour (Mellor and Yamada, 1982), coastal ocean prediction (the Princeton/Dynalysis Ocean Model; Blumberg and Mellor, 1987; Mellor, 1989b), flow in the marginal ice zone (Mellor et al., 1986, Mellor and Kantha, 1989) and tropical ocean simulations (Rosati and Miyakoda, 1988).

The comparative simulative skill of the various models has been discussed by Niiler and Kraus (1977), Martin (1985), Archer (1990) and Mellor (1989a). The SMC models are the most general, but are limited in their capacity to be tuned and tend to be more computationally expensive. The SMC models do not take account of mixing due to internal or surface gravity waves and are thus likely to perform less well when compared with bulk or shear instability models which have this flexibility, *albeit* through adjustable parameters (this is particularly so in the case of level 2 closure). For the one-dimensional situations considered by Martin (1985) the SMC models performed essentially like shear instability models. Mellor (1989a) points out that several of the deficiencies noted by Martin (1985) could be corrected by "introducing" a shear-term parameterization for the effects of internal waves. A further consideration which will be discussed in more detail in a separate paper is the effect of biology on the penetration of short-wave radiation (heating) in the upper ocean. In the tropics, for example, where the vertical mixing of heat and momentum is critical in the simulation of thermal and current structure (Pacanowski and Philander, 1981), we might anticipate that differential heat absorption and consequent modification of the vertical stability would impact on the circulation.

3.1.2 Physical-biological mixed layer models

Models that couple physical and biogeochemical components are needed to interpret, and in the future assimilate, biological and chemical data collected from *in situ* platforms and from remote sensing platforms. There is also a requirement for the simulation and prediction of CO_2 fluxes between the atmosphere and the ocean and for the transport of carbon in the ocean interior. The discussion here will be confined to models in which the emphasis is on the physical aspects of the problem but with some interface to biological processes. Modelling of the biological and chemical processes, and of the oceanic carbon cycle, will be the subject of a separate discussion paper (Merlivat and Vézina, 1992,). Two- and three-dimensional models will be briefly reviewed in Section 6. Archer (1990) gave a general discussion of the role of vertical mixing in biological-physical modelling.

Vertical one-dimensional models have a rich tradition in biological oceanography due chiefly to the perception that biological production and fluxes can be related locally to vertical variations in the physical structure (currents, shear, stability, turbulent kinetic energy, etc.). These developments range from the study of large-scale and seasonal production patterns (e.g., Riley, 1942; Winter et al., 1975; Evans and Parslow, 1985; Fasham et al., 1983; Frost, 1987) and the impact of vertical motions on daily photosynthetic rates (Falkowski and Wirick, 1981; Woods and Onken, 1982; Wolf and Woods, 1988), through to investigations of the physical regulation of phytoplankton vertical structure, nutrient fluxes, oxygen and pCO_2 cycles (Jamart et al., 1977, 1979; Taylor et al., 1986; Musgrave et al., 1988). The models vary considerably in structure and complexity.

New production models based on one-dimensional wind-driven mixed-layer theory and specifications of the vertical nutrient concentration have been used to simulate the upward nutrient flux (Klein and Coste, 1984; Lewis et al., 1986; Chen et al., 1988). Two- and three-dimensional new production models are being developed to simulate nutrient distributions in the ocean thermocline (e.g., Toggweiler, 1989). It may be possible to couple the mixed-layer models for vertical fluxes and the GCMs for transport to simulate upward nutrient fluxes into the photic zone thus yielding (indirect) estimates of the organic carbon inputs to the thermocline and deeper waters.

The majority of mixed layer models assume the effect of the biology on the physics can be ignored. However Sathyendranath et al. (1991), using ocean colour images of the Arabian Sea, have shown that phytoplankton distribution can influence the seasonal evolution of SST. Mazumber et al. (1990) demonstrated significant relationships between plankton biomass, light penetration and mixed layer depth for lake systems, strongly indicating a dependence of mixed layer evolution on the biology. There are presently very few models that incorporate biological feedbacks into the physics. Lewis et al. (1983) and Siegel and Dickey (1987) have produced optical-biological parameterisations which show that vertical heating rates by biological light absorption can be sufficient to generate upward convection in the water column. Simonot et al. (1988) attempted to couple physical and biological processes in a mixed-layer model using different vertical grids for the physical and biological sub-models. Together these and other studies provide strong evidence of a potentially important impact of marine biota on air-sea exchanges of heat and on vertical current structure (through modification of the vertical stability).

3.2 Assimilation and prediction

There have been relatively few studies which attempt to combine mixed layer models with data in an assimilative/predictive mode. The OTIS model of FNOC (Clancy and Pollack, 1983; Clancy et al., 1986; Clancy et al., 1989; Clancy et al., 1990), discussed above in relation to surface fields, combines surface and subsurface data into a mixed layer model of the thermal state. Forecasts between one ingestion period and the next are provided by a mixture of stochastic (e.g. climatological) and deterministic predictions. Gaspar et al. (1990) took the view that remote sensing provides the best opportunity for collecting the data necessary to constrain the evolution of models (wind stress from scatterometers; radiation and SST from AVHRR). The ocean structure was obtained by inverting the thermal evolution equations subject to the surface constraints, thereby providing predictions / corrections to the ocean surface fluxes.

The quasi-operational tropical forecast systems of NMC (Leetmaa and Ji, 1989) and BMRC (Smith, 1991b) both include shear-instability models for vertical mixing. However the role and value of the mixed layer models in these systems is yet to be documented. For example, are the characteristics of a particular mixed layer model important for data assimilation or quality control, and can the model choice impact on the predictive skill of the model? Experience in NWP has indicated that the planetary boundary layer formulation does have a substantial impact on forecast skill, both through its local determination of the planetary boundary layer profile, and through its influence on the large scale flow patterns.

For the tropical ocean prediction problem (see Section 4) there is at least some guidance from the simplified coupled models used in tropical problems (e.g., Cane and Zebiak, 1985). In developing models for interannual variability in the tropical oceans it has been found that the inclusion of mixed layer physics, *albeit* in simplified form, was essential for the successful coupling of the oceanic and atmospheric components. The forecasts are, however, quite independent of oceanic data, relying instead on a projection based on the accumulated information from past wind forcing. That these models have been as successful as they have (UCAR, 1991) raises the possibility that predictive skill (at least in the tropics at around seasonal time scales) may not be dependent on observations of the mixed layer. However it should be borne in mind that the mixed layer models used in the majority of tropical coupled ocean-atmosphere models employ only rudimentary physics and may thus be a poor guide to the utility of mixed layer models in the more general assimilation and prediction problem.

3.3 Network design and quality control for the mixed layer

There are few published accounts of upper ocean models, being used either explicitly or implicitly within larger models, for network design or controlling the quality of data from measurement systems. Phoebus (1990) described the quality control algorithms employed at FNOC as part of OTIS. The main techniques are climatological (first-guess) checks and "buddy checking". Again, we can get some insight into possible problems through the experience of NWP. There, both at the global scale and at regional scales, the experience has been that it is critical that the planetary boundary layer growth and convective activity be modelled well. If, for example, the top of the planetary boundary layer is anomalously high then data at that height may be incorrectly flagged and/or rejected. In the forecasting of fronts vertical mixing appears to be critical, so again the efficacy of the quality control is likely to be impacted if this aspect is inadequate. There is no reason to believe the situation in oceanography will be any different, and it may even be harder (the mapping and prediction of Gulf stream meanders is a good example; Cummings, 1990; Moore, 1991).

3.4 Developments for mixed layer models in OOS

The crucial role of seasonal boundary layers as the "communication medium" between the interior of the ocean and both atmosphere-ocean interactions and land-ocean fluxes over the continental shelves underscores the importance of developing credible parameterizations for vertical mixing. Models for mixing of heat and momentum are at an advanced stage but there remain problems in capturing the evolution of the seasonal thermocline and in taking account of mixing generated remotely (say by storms) but effective locally through the breaking action of internal waves. A great deal of work remains to be done in order to understand the complex physical, biological and chemical interactions within the surface layer. For climate prediction, advances in this area, particularly with respect to the carbon cycle, will be critical.

The design and effectiveness of OSSE/OSE-type experiments should also be addressed. Experience in NWP suggests the ocean boundary layer will be an important component of ocean prediction systems, first through its direct impact locally on model-data conflicts, and second through its impact on the global-scale simulation of currents, heat transport and biogeochemical fluxes. Much of the current data will inevitably be collected in the mixed layer and, if this data is to be used successfully as a constraint on the circulation, the ocean data assimilation systems will need to have good representations of the upper layer physics. The problems associated with sharp fronts, say between coastal and deep waters or in high-latitude regions such as the Southern Ocean, or the patchiness of biological activity/production such as in the North Atlantic spring bloom, pose considerable problems for interfacing models with observations.

Perhaps the severest test of the integrity of ocean mixing models will come with the advent of NOP as in UCAR (1991) and at the various quasi-operational centres. The inadequacies of ocean boundary layer physics will be laid bare by the continual requirement of matching real-time forecasts (rather than hindcasts) against new, independent data.

4. The tropical oceans

The simulation and prediction of climate change in the tropical oceans offers unique opportunities for the development of operational systems. It is the singular character of tropical ocean circulation which largely warrants its consideration as a separate modelling component in the development of OOS.

The evolution of modelling and observation of the tropical oceans is well documented. The planning for TOGA (TOGA, 1985) and the TOGA Numerical Experimentation Group Reports (TOGA NEG, 1989, 1990) gave details of the key problems and advances made through the first phase of TOGA. Several review articles have discussed developments in equatorial modelling (Moore and Philander, 1977, Knox and Anderson, 1985; McCreary, 1985), while Philander (1990) presented an excellent overview of modelling and observational research related to El Niño and La Niña. Charnock and Philander (1989), McCreary and Anderson (1991), Neelin et al. (1991), and the proceedings of the Liége Colloquia (Nihoul, 1985, 1990), gave a broad and up-to-date account of tropical ocean-atmosphere studies. For the specific problem of combining observations and model estimates for prediction, "A TOGA Program on Seasonal-to-Interannual Prediction" (UCAR, 1991) presented a good account of progress to date and highlighted key issues for future development. This document embraced much of which is relevant to the present discussion, namely a description of the simulative and predictive abilities of the present modelling and observing system, an assessment of developments which are required in the future, and a strategy for using models actively in the design of a (tropical) ocean observing network.

4.1 Simulation of the tropical ocean circulation

Knox and Anderson (1985) reviewed the history and advances in equatorial ocean theory. The genesis of the modern approach to equatorial ocean modelling is usually attributed to Lighthill (1969) who demonstrated why an equatorial ocean (in his case the Indian Ocean and Somali Current) could so quickly respond to changes in wind forcing, and that this response may not be locally driven. That is, changes in wind forcing at a particular site (but still within the vicinity of the equator) could generate significant responses in current and temperature at remote sites. This concept generated much interest and activity in the problems of equatorial ocean circulation (see Moore and Philander, 1977) which, together with the growing interest in interannual variability and the ENSO phenomenon, was to lead to the inception of TOGA.

There were many thoughtful papers through this period which are relevant to this document. Busalacchi and O'Brien (1980, 1981) and Busalacchi et al. (1983) applied a reduced-gravity (that is, single vertical mode) model to the Pacific Ocean circulation, and were among the first to critically evaluate model results with observed fields. The hindcasts of pycnocline (or equivalently, sea-level) displacements were able to capture much of the observed variability in sea level and, if pycnocline displacement was used as a proxy for SST, at least some of the variability in SST. McCreary (1976), Cane and Sarachik (1977) and Cane (1979a,b) revealed the important role of equatorial

Kelvin and Rossby waves in the response of equatorial oceans. Gill (1983) used a simple linear model with the long-wave approximation to simulate the Pacific Ocean response during the 1972 El Niño event, using eastern Pacific sea level as the forcing function. Schopf and Cane (1983) redressed the lack of thermodynamics in the reduced-gravity model by including mixed layer physics within the upper layer, adding an extra surface level to accommodate the important influence of Ekman currents off the equator. With only a modest increase in complexity they were able to take account of the key thermodynamic processes which are critical to equatorial adjustment (Schopf, 1983).

This period also saw the first general circulation models of the equatorial circulation being constructed. Philander and Pacanowski (1980) used an idealised equatorial ocean driven by zonal winds to study thermodynamic and non-linear interactions in the spin-up and spin-down (Philander, 1981) of equatorial circulations. These scenarios were likened to the different phases of El Niño. The first realistic simulations of equatorial behaviour were due to Philander and Seigel (1985) (for the Pacific Ocean; see also Philander et al., 1987a, and Philander and Hurlin, 1987) and Philander and Pacanowski (1986) (for the Atlantic). The model included a shear instability vertical mixing parameterization (Pacanowski and Philander, 1981) and unprecedented horizontal and vertical resolution (for OGCM studies) to enable the model to capture the shear and thermal structure characteristic of the equatorial regions. The Philander and Seigel (1985) Pacific Ocean model was forced with NWP analyses of wind stress for the ENSO event of 1982-83 and a parameterized form of surface heat flux in which latent heating (and its dependence on the wind speed) dominated. This simulation captured the broad features of SST and current anomalies through the event.

The proliferation of numerical ocean simulations for equatorial circulation can be attributed in part to the success of these pioneering studies. Philander et al. (1987a) demonstrated the effectiveness of the model in capturing the seasonal cycle of the Pacific and improved our understanding of the complex dynamical and thermodynamical mechanisms which help determine the Pacific Ocean energy budget. Harrison et al. (1989, 1990), Harrison (1989a) and Harrison (1991) showed that Pacific Ocean simulations are quite sensitive to differences in the wind forcing and to details of the surface heat flux parameterizations. Latif (1987), using a slightly different model, also demonstrated a strong sensitivity to the wind forcing. Rosati and Miyakoda (1988) studied the role of high frequency wind variations and of horizontal and vertical eddy parameterizations. With constant mixing and monthly mean winds their model developed systematic errors in several areas of the tropical Pacific; with grid-dependant horizontal eddy mixing, SMC vertical mixing (at level 2½; see Section 3.1.1), and high frequency variability in the wind forcing, the thermal and dynamical simulations were realistic.

Despite the successes of these and many like studies several problems remain. The extreme sensitivity of the models to uncertainties in the surface forcing, both for momentum and heating, severely reduces the confidence in the results. The success of tropical ocean simulation is inextricably linked to the successes and failures of the surface field component determinations (Section 2). The need for temporally consistent surface boundary conditions cannot be over-emphasised. The physics of the models should also be improved.

Most of the models discussed thus far have taken little account of the effect of salinity. Cooper (1988) demonstrated the importance of salinity in a simulation of the Indian Ocean, mainly through its direct contribution to steric height and the resultant geostrophic flow (order 10% of the total). However the more important role may be in its moderation of vertical mixing rates as suggested by the "barrier layer" effect in the western Pacific (Lukas and Lindstrom, 1987; Godfrey and Lindstrom, 1989; Smith et al, 1992). The vertical mixing parameterizations in general need further study (Rosati and Miyakoda, 1988, Smith and Hess, 1992). The role of deep temperatures (below the main thermocline) and interactions between equatorial circulations and mid-latitude circulations (such as might occur in the western boundary currents of the subtropical northwest Pacific) have yet to be fully understood.

It is now becoming apparent that both interannual and seasonal fluctuations in the Pacific are strongly influenced by ocean and atmosphere coupling (Neelin et al, 1991). For this reason the OOS for the tropical regions cannot be developed without due regard for the coupled system. McCreary and Anderson (1991) identified three potentially important mechanisms for atmosphere-ocean coupling in the tropical oceans: the propagation of internal equatorial Kelvin and Rossby waves and the subsequent reflection at meridional barriers (the "delayed-action oscillator"); dual equilibrium states, with a "trigger" switching system; and *in situ* growth of unstable equatorial modes. The linear instability studies of Philander et al (1984), Hirst (1985, 1986, 1988), Battisti and Hirst (1989), and others, showed that instabilities of the mean state could generate interannual variability in coupled models. Schopf and Suarez (1988) attributed the reversal between warm and cold states to the propagation of equatorial Rossby waves and their subsequent reflection at the western boundary.

4.2 Assimilation and prediction in tropical oceanography

The equatorial oceans provided one the first opportunities in oceanography to follow the methodologies used so successfully in NWP and perform numerical ocean predictions (in this context "numerical" implies the use of objective analysis and assimilation techniques). They also provided opportunities for oceanographers to apply newer methods of data assimilation, such as variational techniques and adjoint methods, and perhaps even provide a lead to meteorologists. Ghil (1989) made the case for innovative techniques well, pointing out that oceanographers are handicapped by vastly inferior observing networks and the comparative scales of oceanographic weather. The discussion here will be restricted in the main to applications which have been tested with *real* data, consistent with our commitment here to methods and models which are relevant to the development of an OOS.

Research at NMC led to the first real-time application of equatorial ocean data assimilation and prediction (Leetmaa and Ji, 1989). This application developed from the work of Derber and Rosati (1989) who presented an application of variational techniques to data assimilation in the global domain. In practice assessment of the model was restricted to the equatorial Pacific and, in particular to the latter part of 1979 when the ship-of-opportunity program was beginning to provide partial coverage of the region. It was clear from this limited study that data assimilation in the equatorial regions was both feasible and effective. Leetmaa and Ji (1989) incorporated this scheme to provide monthly hindcasts of oceanographic conditions in the tropical Pacific, incorporating complex quality control measures to isolate poor data (Derber et al., 1990; Leetmaa, 1990). Hayes et al. (1989) showed the model capable of reproducing many of the observed current variations near the equator, although in certain regions (e.g. the southeast Pacific) lack of ingestable information and less-than-perfect model physics led to less satisfactory results. Leetmaa and Ji (1989) emphasised the critical importance of surface forcing in the scheme whereby poor forcing could lead to systematic bias compared with observations. Leetmaa (1990) discussed how such a real-time system could be deployed to assess various aspects of the observing system and how it might be used to provide an effective alternate means for estimating heat and fresh-water fluxes into the ocean.

The TOGA program and the ensuing increased real-time data flow have spawned several other analysis and assimilation programs. The ocean analysis facility at FNOC was discussed in the previous sections. White et al. (1988) discussed the Joint Environmental Data Analysis Centre which was established to provide quality control and analysis of real-time and delayed mode bathythermograph data. The analysis procedures are derived from the methods of optimum interpolation and were first applied in the interpretation of North Pacific (White and Bernstein, 1979) and equatorial Pacific (White et al., 1982, 1985) data. The analysis system at the BMRC is developed along similar lines (Smith et al., 1991), incorporating the results of Sprintall and Meyers (1991) and Meyers et al. (1991) for scales of spatial and temporal variability in the Pacific, and adapting the NWP methods described in Lorenc (1981) to build complex objective quality controls (Smith, 1991a). A numerical model has since been added and a series of hindcasts from 1979 through to 1990 have been carried out to test the analysis-assimilation system (Smith, 1991b). An Atlantic Ocean analysis and assimilation system has also been established at the LODYC, Paris (Morliere et al., 1989) with monthly assimilations and analyses being published in the Bulletin Ocean Atlantique Tropical. Carrington et al. (1990) and Carrington (1991) described research efforts at the UKMO to establish an operational Indian Ocean forecast and assimilation system.

There are several other studies that, while not directly involved with operational centres, have provided insight into the appropriate methods of data assimilation (see also Ghil and Malanotte-Rizzoli, 1991). Philander et al. (1987b) showed that thermal data were extremely effective at initialising equatorial models, but that velocity data were less useful. Moore and Anderson (1989) presented results from an assimilation system for the Pacific Ocean based on a reduced gravity model and successive correction. This study demonstrated that ingested thermal data could quite rapidly correct the model circulation and that this information was retained for extended periods. This problem was re-examined by Sheinbaum and Anderson (1990a,b) who replaced the successive correction analysis scheme with a variational approach. They showed that such a scheme could provide corrections to the model forecast in areas remote from the site of the data. Thacker and Long (1988) and Long and Thacker (1989a,b) used the adjoint method and synthetic equatorial ocean data to investigate the conditions under which a control solution could be recovered. They found surface elevation data needed to be supported by subsurface data if the baroclinic state of the control model was to be regenerated. Bennett (1990) showed that generalised inverse methods are tractable and feasible when combining XBT data and an equatorial model. The key to his technique seems to be the efficient solution of a two-point boundary value problem using representer functions.

The literature on data assimilation and inverse theory for tropical oceans has grown enormously in recent years and, while many of these studies are not directly relevant to OOS at present, it may transpire that some of them will find applications in equatorial oceanography. Ghil and Malanotte-Rizzoli (1991) provided a valuable overview of the application of data assimilation techniques in oceanography, much of which is directly applicable to the present problem. Anderson and Willebrand (1989), the special issue of Dynamics of Atmospheres and Oceans (Vol 13, Nos 3 and 4, Haidvogel and Robinson, 1989), and the report of the workshop on "Inversion of Ocean General Circulation Models" (WCRP, 1989d) together give a comprehensive account of the healthy state of data assimilation in tropical oceanography.

4.3 Tropical ocean observation networks and quality control

Equatorial oceanography and TOGA have been pioneers in the study and design of observation networks, and at least part of the success of TOGA must be attributed to the careful attention paid to these details. White et al. (1982, 1985), Sprintall and Meyers (1991), and Meyers et al. (1991) have used the over-sampled XBT lines of the ship-of-opportunity program to estimate the dominant temporal and spatial scales of the equatorial Pacific Ocean, thereby optimising the information gathered by the broad-scale sampling program. This information is crucial in a program where resources are limited and excessive redundancy means wasted effort.

Dynamical models provide an important feedback of information to the observing system. Existing equatorial ocean analysis and prediction schemes incorporate sophisticated quality control schemes (Leetmaa and Ji, 1989; Smith, 1991a,b), although the efficacy of such schemes would be enhanced by improved model skill and better measurement coverage. Hollingsworth and Lönnberg (1989) and Hollingsworth et al (1986) have emphasised the importance of these elements in quality control of atmospheric data. Leetmaa (1990) has discussed how information provided by the model and, in particular, the degree of compatibility between model forecast and data, can be used to delineate deficiencies in the ocean SST observing network. Leetmaa (1990) also discussed the relative worth of various observation platforms in terms of their impact in the data assimilation system and their value as independent validation of various fields. Derber et al (1990), Smith (1991a) and Smith et al. (1991) have discussed the ability of quality control systems to impact the efficacy of analysis and assimilation schemes.

The TOGA Program on Seasonal-and-Interannual Prediction (UCAR, 1991) emphasises the importance of OSSE/OSEs in observation network design and clearly future OOS enhancements should wherever possible be subject to evaluation in this manner. The only OSSE-style experiments carried out thus far have been of the "identical-twin" variety, but these have not usually been concerned with observation systems *per se*. Moore et al (1987) compared the relative influence of temperature and velocity data in initialising and updating an Indian Ocean model (the data were sampled from a separate Indian Ocean simulation). Temperature data were more effective in setting the model state, principally because of the greater proportion of potential to kinetic energy (Anderson and Moore, 1989). Philander et al. (1987b) also concluded that temperature data could be used effectively to initialise the tropical ocean circulation (again in identical-twin experiments). Miller (1990) investigated the impact the addition of ocean thermal data might have in hindcasts of sea level in the equatorial Pacific. To date this is the only true OSE that has been undertaken for the tropical oceans. His results suggested the TOGA Tropical Atmosphere Ocean (TAO) array would positively impact on hindcasts of monthly mean sea level (a reasonable proxy for equatorial ocean heat content or dynamic height).

4.4 Future developments in the tropical OOS

The prior discussion and UCAR (1991) both underline the need for an increased, positive approach to observing system design through active promotion of OSSEs and OSEs. Although the TOGA program has been largely successful at meeting its half-way goals, the move toward implementing an operational network for post-TOGA has yet to begin. There are a variety of systems presently providing temperature, salinity and velocity information in the tropical regions. These include the ship-of-opportunity network, the TOGA TAO arrays, the Volunteer Observing Ships (VOS) conventional surface measurements, current-meter moorings and drifters for velocity, the island tide gauge network, and the promise of even more and better surface measurements from satellites. The relative worth of each system must be quantified, and the only feasible objective method available at present is impact evaluation in data assimilation systems. This assessment is not likely to be simple, and the results are likely to be somewhat ambiguous in any case. For this reason objective assessment may often be subjugated by evaluations based on subjective scientific intuition. But it is important that the oceanographic community learns to use such tools, and the tropical oceans provide an ideal test bed. The TOGA Program on Interannual-to-Seasonal Prediction (UCAR, 1991) and the TOGA Coupled Ocean Atmosphere Response Experiment (TOGA COARE; TCIPO, 1991) will be important in this learning process.

There has, as yet, been no detailed assessment of the impact of salinity in tropical ocean prediction systems, the principal reason being that little salinity data is made available in real-time. The ORSTOM group have been systematically collecting SSS on ship-of-opportunity lines (Delcroix and Henin, 1989) but to date there has been no attempt to assess the impact of such data in a Pacific Ocean assimilation model. Smith et al (1992) have shown that salinity effects are important for the surface energy and water budget, which would suggest a role in prediction as well.

5. The thermocline problem: eddies, gyres and ventilation

In the processes and modelling chapter of the IPCC report on climate change Cubasch and Cess (1990) introduced discussion of the ocean by dividing it vertically into the seasonal boundary layer, the warm water sphere and deep water. According to their definition the warm water sphere, or equivalently the permanent thermocline water, is that part of the column which is ventilated by the seasonal boundary layer (exchanging heat, salt, nutrients, gases, etc.), and is pushed down to several hundred metres in gyres by the convergence of surface Ekman flow. To the modeller, the permanent thermocline has traditionally been the (sharp) demarcation between the wind-forced upper ocean flow, such as the mid-latitude gyres, and the less energetic deep waters. The problems in modelling and observing the thermocline circulation are compounded by the relatively weak signal of the permanent flow compared to the energetic ocean eddies. Woods (1991) pointed out that the eddies contain around 99% of the oceans kinetic energy. In addition most of the potential - kinetic energy interchange occurs at the smaller scales.

The majority of models are of an ideal-fluid type but, while providing powerful and interesting examples of thermocline circulation theory, they have usually not been tested in real ocean problems. This theory is discussed in Pedlosky (1987) and Gill (1982) and was the subject of excellent reviews by Pedlosky (1990) and Huang (1991). The class of models considered in this section tend to assume the existence of the thermocline as a matter of course, rather than considering its genesis and maintenance under the unified effect of surface wind and buoyancy forcing. The interested reader is referred to Huang (1991) for an account of these aspects.

The physical and chemical properties of the warm water sphere have been determined over many years by the gradual leakage from the seasonal layer. Western boundary currents such as the Gulf Stream, large-scale mid-latitude gyres, and mesoscale (tens of kilometres) eddies are all part of the thermocline circulation. The circulation is no longer dominated by vertical mixing (as in the seasonal layer) but is in near-geostrophic balance, the perturbations being induced by, among other things, convergences and divergences due to surface wind and buoyancy forcing, and inherent instabilities in the mean flow. This near-geostrophic balance and the absence of deep convection has enabled an hierarchy of model approaches ranging from simple Sverdrup balance (Sverdrup, 1947) and boundary layer models (Stommel, 1948; Munk, 1950) through the innovative ventilation models of Luyten, Pedlosky and Stommel (1983) and Woods (1985), to the complex and sometimes eddy-resolving ocean general circulation models (e.g., Cox and Bryan, 1984; Cox, 1985). Our understanding of the thermocline circulation has benefited from research at all planes of complexity but, in order to keep the present discussion manageable, we limit our attention to just a few of these studies.

The need for the models to be relevant to the development of a conceptual design for an OOS immediately shifts the focus toward numerical models, though usually not of the general circulation class (these will receive greater attention in the following section). The dynamic models usually make explicit the notions of flow following isopycnal surfaces (hence reduced-gravity models, isopycnic models) and of the near-geostrophy of thermocline currents (hence the quasi-geostrophic assumption; again refer to Pedlosky, 1987, or Gill, 1982, for details). For water mass formation (i.e. the acquiring of characteristic physical and chemical properties) the layered ocean concept is extended to allow for ventilation at locations where the thermocline layers outcrop and intersect the seasonal boundary layer (Luyten et al., 1983; Huang, 1991) and subsequent subduction beneath the lighter layers above. However it should be recognised that the idealisation of the motion away from the surface as preserving density is too simplistic. The results of Talley (1988) suggested potential vorticity is not exactly conserved along flow lines and that buoyancy forcing of subducted layers cannot be ignored (Pedlosky, 1990). Indeed in reality the fields of density and velocity are non-linearly coupled and to understand the distribution of either field requires understanding of the full temporal and spatial structure of the ocean circulation. Nevertheless these simplified models have much to contribute to the development and implementation of an OOS and it is toward this contribution that the present discussion is directed. WOCE has outlined a major effort to enhance our understanding of the mechanics of ventilation and subduction (the Subduction Experiment; WCRP, 1988b,c; Jochens, 1990), the results of which will play a large role in determining the future path of research.

5.1 Interpretation and Simulation

In this subsection we briefly report on activities in interpretation of data and model simulation which have impacted our understanding of the thermocline circulation. While inverse models are the most general interpretive tool, and clearly have a major role in diagnosing the thermocline circulation, we postpone a discussion of their role until the deep water section (Section 6.2). The calculation of dynamic (or steric) height coupled with an assumption of geostrophic balance constitutes the simplest interpretive modelling tool for dynamical oceanography (Pickard and Emery, 1982). Coupled with comprehensive gridded oceanic data sets such as Levitus (1982) or Gordon and Molinelli (1982) the dynamic method can be a simple, but powerful interpretive tool (Gordon et al., 1978; Levitus, 1984; Godfrey, 1989). The weakness of the method lies mainly in the need to assume a level of no motion somewhere below the thermocline. The solution to this dilemma is to either measure the currents directly at some level, or include constraints in addition to that of geostrophy. This extra level of sophistication is pursued in more detail in Section 6.

We order our discussion of simulation tools according to the particular simplifying assumptions employed for each model. To model the oceanic gyres, mesoscale eddies and the ventilation/subduction process within a single model framework would require resources on a prohibitive scale, and might tend to obfuscate rather than illuminate the fundamental processes. So it is usual to compromise and simplify the problem by taking explicit account of the nature of the thermocline flow. The approaches tend to divide into either mesoscale eddy genesis tools (Robinson, 1983) or subduction tools (similar in concept to Stommel, 1979 and Luyten et al, 1983; see Huang, 1991), usually with the implicit consideration of gyre recirculation in the Sverdrup regime (Pedlosky, 1990).

(a) Low vertical resolution models

The simplest solution to the resource dilemma is to limit the physics and vertical resolution. The reduced gravity model discussed in the context of equatorial modelling is an example. The numerical solution of such systems is highly efficient and enables truly eddy-resolving horizontal resolutions (Hurlburt, 1989). Kindle and Thompson (1989) utilised such a configuration in their study of 26- and 50-day waves in the Indian Ocean. Hurlburt et al. (1989) and Kindle et al. (1989) discussed a North

Pacific Ocean simulation which included estimation of the Indonesian Archipelago throughflow (the fine resolution enabled unprecedented resolution of the complex geography of the throughflow region). Such models include sea surface elevation explicitly and are thus well suited to simulations of sea level variability and are potential users/assimilators of sea surface height data (Hurlburt, 1986; Kindle, 1986).

(b) Quasi-geostrophic models

These models are founded on the principle that thermocline motions are in near-geostrophic balance, so that the quasi-geostrophic approximation to the full equations is valid (Pedlosky, 1987). A numerical model consistent with these principals was first developed by Holland (1978) and, as a consequence of the greatly reduced complexity, enabled eddy-resolving studies, mostly within idealised domains (Holland et al., 1983; McWilliams et al., 1978). While such models are limited in their application (e.g. no convection; not applicable at equator) they have provided dynamical and kinematic insight that is not available from other models. For example Schmitz and Holland (1982) were able to make comparisons between simulated mesoscale variability and observed variability in the vicinity of the Gulf Stream. Such models have enhanced our understanding of baroclinic instability in the oceans and of the complex potential and kinetic energy exchanges which control the generation and decay of mesoscale eddies. The quasi-geostrophic models have made a valuable contribution to the understanding of mesoscale and gyre-scale processes, a knowledge which is now being successfully applied to eddy-resolving OGCMs (e.g., Bryan and Holland, 1989; Böning et al., 1991).

(c) A balanced model for ocean circulation

Gent and McWilliams (1984) have derived a set of balanced model equations by combining an exact heat equation with truncated vorticity and divergence equations, reducing the degrees of freedom of the primitive equations by 1/3. The truncated divergence equation may be used in either linear or non-linear form and is now diagnostic (no gravity waves). The model resolves mesoscale turbulence and diabatic processes (c.f. quasi-geostrophic model), and appears to follow the primitive equation slow manifold (e.g. Gulf Stream meanders and ring shedding) more closely than its quasi-geostrophic counterpart. The reduced physics and associated saving in resources make the balance equation models a viable alternative for climate studies, for example in the study of sub-grid scale parameterizations.

(d) Isopycnic models

This class of model makes explicit use of the fact that the preferred plane of flow is along the isopycnal surfaces; the fixed vertical grid of the primitive equation models is replaced by a set of isopycnic (material) surfaces, in essence a Lagrangian approach to the vertical coordinate (see Huang, 1991, for an excellent account of the development of such models). This approach can be traced to Parsons (1969) who successfully used a two-layer model to describe the separation of the Gulf Stream. Bogue et al. (1986) have compared the Parsons model solution and a one-layer model for isopycnal outcropping with good agreement. Bleck and Boudra (1981) introduced a hybrid isopycnic coordinate model to study mesoscale frontogenesis and the dynamics of the Agulhas Current retroflection. The model was limited in its treatment of layer outcropping and the intersection of layers with topography, but nevertheless has found wide ranging applications (e.g. Bleck et al., 1988; see also Boudra, 1989). Huang and Bryan (1987) used an isopycnic model to study wind-driven gyres in a non-eddy resolving climate framework with substantial isopycnal outcropping. This model has been extended to include thermocline ventilation, reminiscent of the Luyten et al. (1983) model. The model is able to produce the basic features of thermocline ventilation and water mass formation.

These models are being implemented with realistic stratification and Ekman pumping in order to test the ideas of Iselin (1939), who one of the first to note that the acquired temperature and salinity properties of thermocline water are related to the wintertime conditions at the outcropping point. The model developed by Woods (1985) examines the connection between subducted waters and penetration of wintertime mixing. Oberhuber (1991) has also developed an isopycnic model which has recently been applied in a coupled atmosphere-ocean-cryosphere context (Oberhuber et al., 1991). Bleck and Boudra (1986) introduced a pure-isopycnic version of the earlier hybrid model, outcropping being accommodated through the Boris and Book (1973) flux-corrected transport algorithm. The model has been generalised to include topographic and thermohaline driving, making it suitable for subduction studies and coupled model work. Smith et al. (1990) carried out experiments with a seasonal wind-driven isopycnic coordinate model and found the model capable of reproducing the major features of the North Atlantic circulation, including western boundary current separation and a Labrador current.

In addition to these conceptually simpler models there are models based more on the general circulation model approach. These are particularly well suited to thermocline circulation and subduction experiments, some of which will be discussed in the deep water section. Still other models (e.g. the model of Blumberg and Mellor, 1987) have been developed for confined basin and coastal studies but are now finding applications more aligned with large-scale ocean studies.

5.2 Assimilation and prediction of the thermocline circulation

Assimilation and prediction research has focussed on the eddy field in the main, although some of the inverse modelling studies are relevant to subduction (Section 6.2). The goals for the thermocline/warm water sphere are somewhat different from those of equatorial prediction. Here the aim is more closely aligned with weather prediction in meteorology, but now the weather is provided by mesoscale eddy activity, and the predictability time scales are those of mesoscale eddy generation and decay (i.e. weeks to months). So the model should be eddy resolving and efficient, and be commensurate with the data being ingested. For these reasons the quasi-geostrophic formulation has been favoured in the majority of applications with particular emphasis on methods for ingesting altimeter data.

The methods used for assimilating data vary from blending and nudging techniques (e.g. Malanotte-Rizzoli and Holland, 1986, 1988, 1989), sequential optimal interpolation (e.g., Robinson et al., 1986; White et al., 1990a,b,c), Kalman filters (e.g., Bennett and Budgell, 1987; Miller, 1989; Gaspar and Wunsch, 1989) and variational methods (e.g., Long and Thacker, 1989a,b; Moore, 1991). The principal motivations for data assimilation come from the prospect of having global, near-synoptic altimeter data coverage, and from the pressing need for oceanographers to extract maximum information from a sparsely distributed *in situ* observation network (Ghil and Malanotte-Rizzoli, 1991).

Research in the assimilation of altimeter data has mostly been conducted with identical-twin configurations. Marshall (1985) used a quasi-geostrophic model to show that altimeter data assimilated into a model could improve the estimate of the geoid. Webb and Moore (1986) , Hurlburt (1986) and De May and Robinson (1987) showed how altimeter data could constrain the thermocline and deep ocean flow through its projection onto the vertical modes. White et al. (1990a,b,c) used the Holland (1978) eddy-resolving quasi-geostrophic model to investigate the impact of continuous assimilation (by optimum interpolation) of (simulated) GEOSAT altimetric data. They found the data effectively constrained the linear part of the model domain but was unable to constrain the non-linear portion after initialisation because of aliasing problems. Furthermore they showed that only wavelengths longer than the Nyquist sampling wavelength (twice the GEOSAT track separation) were positively impacted by assimilation. Kindle (1986) also addressed the problem of sampling frequency/ spacing versus spatial scales of the mesoscale field, concluding that altimeter sampling must at least match the outer eddy radius if the mesoscale field is to be reproduced. Holland (1989) combined GEOSAT data with a quasi-geostrophic model, using a simple nudging technique, to predict the surface and deep eddy field and mean flow of the Agulhas retroflection region. The GEOSAT sampling in this region is seemingly sufficient to infer structure at the eddy scale. Ghil and Malanotte-Rizzoli (1991) provided an informative appraisal of the relative merits of direct ingestion of data versus blending/nudging techniques.

Robinson and Walstad (1987) discussed a model designed for data assimilation (Carter and Robinson, 1987) and forecasting. The model has been applied to both the Californian Current (Robinson et al., 1986) and to the Gulf Stream (GULFCAST; Robinson et al., 1989a,b). Their procedure utilised bathythermograph data, altimeter data and, in particular, AVHRR (SST) data to resolve the path and features of the Gulf Stream (hence "feature modelling"). They were able to produce weekly forecasts of the Gulf Stream path including meandering and ring shedding. Moore (1991) used a similar model and data but adopted adjoint methods in place of the Carter and Robinson (1987) optimal interpolation technique. The model was able to correct for large errors in the speed and position of the Gulf Stream and demonstrated the ability of the adjoint method to transfer information into data sparse regions. The advection of information in space and time (c.f. statistical extrapolation in conventional optimum interpolation) is an important advantage of this approach. However, in common with all regional models of the atmosphere and ocean, the uncertainty in the open boundary condition (i.e., the consideration of information from outside the domain which is advected and propagated through the boundaries) is important in determining error growth.

The assimilation of observations from the conventional observing network poses a contrasting problem since we now have direct measurements of subsurface structure, but only in a sparsely distributed network. Malanotte-Rizzoli and Holland (1986, 1988) concentrated on the problem of assimilating hydrographic data into both steady and transient, eddy-resolving quasi-geostrophic models. They concluded that such data might constrain the long-term bias of the model (i.e. the model and "observed" climatologies will be similar) but that it would be unable to resolve oceanic weather. Malanotte-Rizzoli and Holland (1989) addressed the same problem, plus that of initialisation, but in a primitive equation model. They found that baroclinic information (i.e. hydrographic data) could quickly excite a realistic barotropic field, but that depth-averaged data were unable to constrain the baroclinic component. (Initialisation becomes an issue if, after data insertion, the model is out of balance; this is not an issue with balanced equation or quasi-geostrophic models since their formalism ensures balance by eliminating waves on the fast manifold.)

The growth of interest and knowledge in assimilation methods for the thermocline circulation is attested by the large number of articles published in recent years (Haidvogel and Robinson, 1989; WCRP, 1989d; Anderson and Willebrand, 1989; the International Symposium on Assimilation of Observations in Meteorology and Oceanography, WMO, 1990; Ghil and Malanotte-Rizzoli, 1991). A range of data and models have been studied, and several different data-model merging techniques have been used. This variety of approach is invaluable if the oceanographic community is to learn the optimal strategy for combining information from observations with the interpolative and interpretive skill of models.

5.3 Observing network design and quality control

GULFCAST (Robinson et al., 1989a,b) is a good example of the design and implementation of a quasi-operational forecasting system with feedback to the observing network. The key data in the Gulf Stream observing network were delineated by repeated trials with successively enhanced systems. By studying how the forecast improved or degraded when a particular system or technique was added (e.g. GEOSAT data in the Moore, 1991 study) they learned increasingly more about both the modelling and observing systems. In essence they were performing OSEs.

The studies with simulated altimeter data (e.g. Webb and Moore, 1986; White et al., 1990b,c) are like OSSEs, but in this case it is a "with or without all data" style experiment. To date no studies have looked at the case where simulated (e.g. altimeter) data is withheld from an existing non-trivial data assimilation system (rather than a data-less "control" model). Furthermore most of the studies have considered the altimeter data to be perfect (no noise or bias; White et al., 1990c do consider the addition of noise), and have thus not addressed the problem of quality controlling in a quasi-real-time situation (such problems have plagued NWP in the use of vertical temperature sounding data). This latter problem is not trivial. In all likelihood the number of altimeter data will be insufficient to define the eddy field and, as with any under-sampled system, this will make it make it extremely difficult to quality control and remove bias from an inevitably noisy system.

In the sense that all interpolation methods are sensitive to the temporal and spatial resolution of data, most of the studies cited above could be said to have relevance to array design. Bennett (1985) specifically looked at the question of observation array design in the context of inverse methods. The success of models in resolving particular scales, as in the Holland (1989) and White et al. (1990a,b,c) studies, or in transporting information in time or space (Moore, 1991), all impacts on the design of observing networks. Ultimately, however, the answer to the network design problem for the thermocline circulation will depend on exactly what questions are being asked and the details of the accompanying specifications. If the requirement is to resolve eddies then the existing research is well on the way to providing a prescription, but perhaps not a solution to the logistical and implementation problems (i.e. a cost effective means for the requisite sampling density and rate). If the requirement is to delimit frontal structures and, say the outer and inner boundaries of the Gulf Stream, then a great deal of work is yet to be done. There is confidence, given sufficient resources, that we may be able to forecast the broad-scale weather patterns in the ocean (e.g. Gulf Stream meanders and ring movement) and, with further research, extract the weak signal of the large-scale pattern from the noisy mesoscale eddy field. But forecasts of the genesis and passage of fronts (for example) may require a great deal more research.

5.4 Toward operational thermocline prediction

The promised growth in non-conventional oceanographic data, such as sea level estimates from altimeters and wind-stress from scatterometers, is clearly an important part of the prediction problem for the thermocline circulation. It remains to be determined what level of sampling is required to constrain the gyre circulation or the eddy field. The temporal and spatial scales of ocean weather make resolution of the circulation by conventional measurements unlikely, but they will almost certainly remain important as ground truth/validation points for predictions based on non-conventional data. The research to date suggests multiple altimeters may be required to pin down the mesoscale field, but at this time it is not clear that such resources are going to be available even for a short research period.

Resource limitations are an issue for both the subduction and dynamical oriented streams. Trials with isopycnic models have been promising but much remains to be learnt of the fundamental processes by which water masses acquire their essential characteristics. Temporal effects and sub-surface buoyancy forcing are two aspects which provide an immediate challenge. Theoretical modelling has already provided excellent guidance in this problem (Huang, 1991; Pedlosky, 1990) and, it is to be hoped, will continue to do so in future. Unrealistic rates of formation, and unrealistic water mass characteristics are unfortunately a feature of most global ocean climate models and, while increased resolution will partially alleviate the problem, a great deal of experimentation with process models is still required. The data to design, test and extend these models must be gathered. Eddy resolving studies are in the main confined to truncated or simplified (e.g. quasi-geostrophic) configurations where resource requirements are substantially reduced compared to OGCMs. Such models have been thoroughly tested against primitive equation models in like domains (usually idealised basins), but it remains to be seen whether they are the good analogues they appear to be under more general conditions (thermohaline forcing, finite/steep topography, deep & shallow convection). Uncertainty in the lateral (open) boundary conditions, and in the initial conditions, remains a problem for regional models, particularly in respect of their influence on the growth of errors. A similar uncertainty exists for the upper boundary condition for global and basin-scale models of the gyre recirculation and ventilation and subduction processes.

For the non-thermodynamic elements of the system research is under way to assimilate data in physical-biological models (two- and three-dimensional models are discussed briefly in Section 6 and in detail in Merlivat and Vezina, 1992). An example is the development of techniques to assimilate ocean colour measurements (a proxy for phytoplankton). A problem that must be faced in such systems is that of initialisation. Introduction of information on one component of the ecosystem immediately creates imbalances, and the remaining components must be adjusted to maintain equilibrium. Meteorologists and oceanographers have encountered similar problems with respect to physical and dynamical variables (Daley, 1981; Malanotte-Rizzoli et al., 1989). The use of variational and adjoint methods for assimilating a time-sequence of data appears to have removed some of the problems associated with initialisation and it may be that if such methods (specifically, best fit solutions to all controlling variables) can be applied in physical-biological models then they too will suffer less from gross imbalances between the system components. However the very nature of biological and biogeochemical systems ("patchiness"; rapid growth and decay; sharp gradients) makes them an imposing challenge. These issues will be taken up again in a separate paper.

6. The deep water circulation

The motivation for considering the deep waters as a separate component is provided by their role in long-term climate change (Cubasch and Cess, 1990) where they are considered as the "memory" of the climate system. The global redistribution of heat, freshwater, and dissolved chemicals (e.g. carbon dioxide) through the deep ocean is a climate controlling process and one that will need to be simulated well if we are to describe the present state and future evolution. For the OOS and the Global Climate Observing System (GCOS) the deep water sphere is arguably the most critical component of all. The discussion here will concentrate on large temporal and spatial scales. However it is important to keep in mind that the large scale circulation is subject to forcing by the faster time-scale components considered previously (for example, Ekman pumping and subduction of heat and chemicals through the thermocline, and high latitude deep thermohaline convection) and by surface and bottom effects at much finer spatial scales.

Once again there is considerable overlap between issues considered previously (e.g. eddies, water mass formation) and those that are relevant here; Likewise the demarcation between models of the deep ocean and seasonal and thermocline models is indistinct. In general the deep ocean is the domain of OGCMs and inverse models since simulation and understanding of the "equilibrium" state of the oceans is the primary consideration. Nevertheless it should be borne in mind that the oceans being sampled now and in the OOS are in all likelihood not in equilibrium, but in a continuous state of (slow) change. As was the case for tropical ocean models, it is difficult to consider global oceans without including ocean-atmosphere interactions (that is the global climate system; see WCRP, 1991a).

If equatorial ocean modelling for the OOS was in essence a discussion of TOGA modelling activities, then deep ocean modelling is largely a discussion of WOCE-related activities. The International WOCE Implementation Plan (WCRP, 1988b,c), and various national plans (e.g. Jochens, 1990) provided a good coverage of the present status and priority issues. The problem can be conveniently divided into prognostic models and inverse models. Consistent with the format of previous sections prognostic models will be the subject of Section 6.1 (interpretation and simulation) while inverse models will occupy the bulk of the discussion of Section 6.2 (assimilation and prediction). While this division is convenient it is by no means straightforward. For example, increased carbon dioxide experiments are usually described as "predictions" though they are forced by some (time varying) prescribed concentration of greenhouse gases. Inverse models, on the other hand, could equally be thought of as interpretation tools since they are aimed at revealing the equilibrium circulation given a certain set of constraining observational and thermodynamic relationships.

6.1 Ocean general circulation model simulations

The development and application of OGCMs has been covered in several technical papers (Bryan, 1969; Semtner, 1974; Hasselmann, 1982; Cox, 1984; Han, 1984), texts (e.g. NAS, 1975; O'Brien, 1985, Washington and Parkinson, 1986, Anderson and

Willebrand, 1989; Philander, 1990) and review articles (Holland, 1977, 1979; Bryan, 1979; Meehl, 1990). This section will concentrate on milestones which marked new levels of model sophistication and understanding of the deep ocean circulation, and on some recent applications.

6.1.1 Early developments in ocean general circulation modelling

The "beginning" of numerical modelling for the large-scale ocean circulation is usually attributed to Bryan (1963) who followed the lead of atmospheric GCM research and used the barotropic vorticity equation to model the oceanic circulation in a rectangular basin. (Sarkisyan, 1962, 1975 was another pioneer in this arena). The first global model with sufficiently general numerics to take account of real geometry and topography was presented by Bryan (1969), later updated to include better treatment of islands and improved efficiency on vector machines (Semtner, 1974). Holland (1967) applied similar models in idealised basin studies. At the time of "The Numerical Models of Ocean Circulation" meeting in 1972 (NAS, 1975) computer power was an extremely limiting factor in the design of global applications. Nevertheless that meeting introduced the first attempts at modelling the baroclinic response of ocean models to wind forcing in realistic domains (Takano, 1975; Cox, 1975). At that time the resolution was necessarily coarse (order 2°), the integration periods were short, and horizontal eddy parameterizations were over-dissipative. Nevertheless many of the essential features of the circulation were captured, such as western boundary currents and the Antarctic Circumpolar Current.

Bryan et al. (1975), using essentially the same model as Cox (1975), published results from the first global coupled ocean-atmosphere model. While the scope of the study was limited the oceanic component did reproduce reasonable salinity distributions, such as the observed Atlantic-Pacific difference, and a credible dynamic circulation and thermohaline meridional overturning. The complexity of this study led Bryan and Lewis (1979) to examine and analyse the oceanic component in more detail, enabling somewhat finer resolution and seasonal forcing. The Bryan and Lewis (1979) study remained the benchmark for stand-alone global ocean simulations for many years (see also Bryan, 1979, Bryan, 1982a,b). The model was forced by Hellerman (1967) winds, and surface temperature and salinity were relaxed toward Levitus and

Oort's (1977) climatology. The integrations continued to near-equilibrium. The observed and computed potential temperature and salinity cross-sections were in reasonable accord with observations although the thermocline was both too deep and too thick, and the deep water too warm (Bryan, 1979). This work introduced improved techniques for analysing oceanic simulations and assessing their sensitivity to parameterizations and forcing. For example, Bryan and Lewis (1979) showed that the thermocline depth is directly related to the strength of the wind forcing and to the eddy mixing parameterizations. The results demonstrated the importance of meridional oceanic cells (akin to their atmospheric cell counterparts) in transporting heat toward the poles and transferring (relatively warm) surface water from the summer hemisphere to the winter hemisphere (Bryan, 1982b). The poleward heat flux estimates were consistent with independent estimates from atmospheric and oceanic data.

Several other groups were beginning to implement global ocean models at about this time, mainly with a view toward coupled ocean-atmosphere-ice systems. Washington et al. (1980) and Meehl et al. (1982) developed a coarse resolution ocean model (5° by 4 levels) and tested its sensitivity to the magnitude of the vertical mixing and horizontal diffusion parameterizations, and to the wind forcing. Meehl et al. (1982) pointed out the importance of seasonally varying surface wind-stress and heat flux conditions, particularly for the oceanic heat storage and transport. Han (1984) presented a numerical world ocean general circulation model, forced by fluxes derived from the Esbensen and Kushnir (1981) climatology, and obtained realistic temperature and salinity fields. An over-strong equatorial upwelling led to anomalous cooling in the equatorial Pacific, and limitations on resolution resulted in too coarse western boundary currents (Han et al., 1985). Semtner (1984, 1986a,b) assessed developments in ocean circulation modelling, including numerical methods and tuning of non-eddy resolving models. Cox (1984) presented an updated version of the GFDL code for use by the ocean modelling community, an important milestone in the development and wider application of OGCMs in climate research.

6.1.2 Current OGCM activity

In discussing the current state there are several distinct strands to the research activity that warrant attention. First, with the growing concern in climate and climate change, OGCMs have been deployed in a range of coupled atmosphere-ocean(-cryosphere) configurations in an attempt to understand the coupled climate system and diagnose its sensitivity to anthropogenic forcing. The range of models employed in these studies spans all constituents of the ocean system as defined in Section 1 but there is good reason to believe that the deep water component is especially significant. Though the heat capacity of the upper three metres of the ocean is equivalent to that of the entire atmosphere, it is the ability to sequester this heat in the deep ocean and transport it to higher latitudes which is the key to the coupled atmosphere-ocean system (Bryan et al., 1988). Another approach has been to use the increased computer power and improved numerical formulations to increase global model resolution and enable explicit representation of mesoscale eddies in ocean-only simulation experiments. This activity is more closely aligned with the aims of WOCE, furthering our understanding of the world ocean circulation and producing more realistic simulations of the velocity, temperature, salinity and other constituent fields of the circulation. Finally, there has been important progress in the application of OGCMs to tracer and biogeochemical problems, once more encouraged by the growing interest in climate and climate change. For the OOS this is an area of special interest. These different aspects will be covered in more detail in the following sub-sections.

6.1.3 Ocean only simulations

Together with the application of OGCMs in coupled climate simulations there has been considerable recent activity in prescribed surface forcing (ocean-only) experiments, mostly associated with WOCE. A large part of this growth, particularly within the international ocean modelling community, can be directly attributed to the ready availability of the GFDL ocean model code (Cox, 1984) and the continuing free exchange of enhancements and experiences with that code (now represented by the Modular Ocean Model (MOM) version of the GFDL code; Pacanowski et al., 1991). Nevertheless it is important that a variety of models be used if only to ensure that model intercomparisons are meaningful and not simply a self-congratulatory exercise.

The Semtner and Chervin (1988), Hasselmann (1982) / Maier-Reimer et al. (1982) and Haidvogel et al. (1990) models are good examples of such diversity.

The following discussion is not a comprehensive account of world ocean modelling but rather an attempt to convey the scope and capabilities of the most advanced models in use today, and to give an impression of the range of models being used. Yet again, it is important to emphasise that issues discussed here transcend the artificial boundaries imposed between the different oceanic components, and that considerations in the surface, seasonal layer and warm ocean components, and in particular research on improved parameterizations, will impact directly on the world ocean models. The canonical world ocean model for OOS in the near-term will likely be an amalgam of the following models combined with new initiatives in parameterization, etc.

(a) The Community Modelling Effort for WOCE

This Community Modelling Effort (CME) aims to "design and execute a series of baseline calculations of the wind- and thermohaline-driven, large-scale ocean circulation, to make comparisons of these simulations with observations, and to evaluate the performance of the models and identify needed improvements." While CME is basically a response to Goal 1 of WOCE, the experience of CME could also be viewed as a baseline modelling study for the OOS. The focus is on basin-scale, eddy resolving models of the wind- and thermohaline-driven ocean circulation. The first experiment is a simulation of the North Atlantic, including realistic geometry and topography, salinity, and seasonally varying wind and thermohaline forcing (innovative in the context of eddy-resolving models).

The Bryan-Semtner-Cox model is being incorporated in both medium (1 degree, 20 levels) and fine (1/3 degree, 30 levels) resolution configurations. The model spans 15°S to 65°N, including the Gulf of Mexico and Caribbean Sea (but excluding the Mediterranean), uses rotated isopycnal coordinates (at low resolution) and the Camp and Elsberry (1978) bulk mixed layer (F. Bryan and Holland, 1988, 1989; Jochens, 1990; Spall, 1990). This model will enable a thorough and detailed investigation of the relative roles of the mean flow and eddy fields in the circulation, particularly in respect of thermohaline balances, heat transport and thermocline ventilation. Preliminary results show realistic spatial and temporal surface temperature patterns, vigorous eddy activity and sharp frontal features, a seasonally varying equatorial circulation with "21-day wave" instabilities, and a realistic flow field. Spall (1990) compared the model results with data from the Canary Basin and found the model introduced fine horizontal and vertical features which were not present in the initial condition but which were in accord with known characteristics of that region. In some cases the model impact was negative, particularly in regions influenced by the Mediterranean salty outflow and in respect of the eddy kinetic energy.

The sensitivity of the simulations to the resolution, surface forcing, various parameterizations and the open boundary conditions will be the subject of detailed analysis and further experimentation. Of the various controlling factors the surface forcing would appear to be among the most poorly defined. The Hellerman and Rosenstein (1983) winds, while perhaps adequate for low resolution models of the 1980's, have neither the accuracy (Harrison, 1989b) nor the resolution required by such models. Furthermore the prescription for surface fluxes of heat and freshwater seem badly mismatched with the sophistication of the CME and like models.

The experiences of "community" modelling at this scale provide an ideal prototype for modelling within the context of the OOS. In addition to the experiments mentioned above several very fine resolution runs with improved northern boundary conditions, different friction coefficients, and different forcing are being run at the IfM Kiel (Böning et al., 1991). The design, running and analysis of such an experiment is not a trivial exercise and requires careful planning and coordination, as well as a will to communicate and combine resources over the international ocean modelling community. Even at basin scales, the resource requirements and data handling far exceed the capacity of any individual or group. For a global model at similar resolution, with data assimilation and quality control facilities, the requirement may be an order of magnitude larger.

The CME has provided considerable experience with the management, archiving, analysing, and presentation of results from such a model. As any operational meteorological centre will no doubt testify, the management and archiving of model integrations and output requires an enormous contribution of time and manpower. The shear volume of numbers produced in such an exercise precludes traditional methods of analysis. There is a need for new techniques for visualisation and synthesis of results for human and machine consumption.

(b) The Fine Resolution Antarctic Model: FRAM

FRAM is an initiative by United Kingdom scientists to address some of the problems identified in Core Project 2 of WOCE (WCRP, 1988b) and, like CME, is built around a "community" approach to the design, implementation and analysis of the model. FRAM is a primitive equation model of the Southern Ocean from 24°S to the Antarctic continent and is developed from the Cox (1984) version of the GFDL code. The horizontal resolution is ½° longitude by ¼° latitude (thus enabling explicit resolution of eddies), and there are 32 levels in the vertical with high-quality representation of bottom topography. The surface forcing strategy is similar to that used in CME (FRAM intends to incorporate Esbensen and Kushnir, 1981, flux estimates). Further details and background are given in Killworth and Rowe (1987), WOCE (1988a), Killworth (1989), de Cuevas (1990), and The FRAM Group (1991).

Unlike the CME, the FRAM project has limited prior experience on which it can draw and is concentrating on a region which is relatively poorly observed. The exciting aspect is that the results from the model are potentially more valuable since they could bridge a large gap in our understanding of the World Ocean circulation. A substantial proportion of the initial effort was devoted to testing the model, particularly in respect of topographic effects. The model is initially run in a robust diagnostic mode for several years, relaxing toward Levitus' (1982) annual mean fields. Surface wind forcing is then (gradually) introduced, first as an annual mean then with seasonal variations. The northern boundary is open (Stevens, 1991). Sharply changing bathymetry and barotropic flow-bathymetry interactions can lead to unacceptably large errors in the flow field (Killworth, 1989). With careful attention to the smoothness of the bathymetry and to the spin-up strategy realistic flow and thermohaline circulation patterns were achieved. However it is also clear from direct observations that the fine detailed structure of the bathymetry (particularly trenches and passages) is highly correlated with the deep current structure and without this structure important currents, particularly those transporting Antarctic Bottom Water away from the Antarctic continent, will be missing from the model. The degree to which this omitted detail impacts the general circulation has not been determined.

Sensitivity to various sub-grid scale parameterizations and to the open and surface boundary conditions is also yet to be determined.

The Antarctic Circumpolar Current (ACC) and its interaction with major topographic features such as the Kerguelen-Gaussberg Ridge, Campbell Plateau, the mid-ocean ridge of the South Pacific and Drake passage are all realistically represented. The main regions of eddy activity are in the Agulhas Current region and along the path of the ACC (there is also evidence of a filament-like structure to the ACC). With seasonal forcing there has been an increase in eddy intensity and the ACC transport through Drake Passage is oscillating around 160 Sv. The results from these integrations have recently been made available in atlas form (Webb et al., 1991).

Like CME, FRAM is extremely demanding of human and machine resources and could not be run outside a "community" ocean modelling environment. Key elements of the continuing development are the specification of surface wind and thermohaline forcing as FRAM is particularly handicapped by the poor state of knowledge of these fields, particularly during winter-early spring. The northern (open) boundary condition (Stevens, 1991) and interfacing with a snow and ice model are also high priorities. Considerable effort has already been expended on developing analysis and visualisation tools.

(c) A global eddy-resolving model

The development and implementation of the Semtner and Chervin (1988) model (hereafter SC88) is significant for its design (specifically for modern supercomputers) and for being the first global (almost) eddy-resolving study (resolution of ½° x ½° globally. The eddy-rich structures in the western boundary currents and circumpolar regions, and the suggestion of a Pacific-Indian-Atlantic conduit in NADW formation are just two facets among many which warrant special consideration. The model derived from the Semtner (1974) and Cox (1984) versions of the GFDL code. Semtner (1986b) described a modified formulation of this code and provided a background to the logical development of the SC88 code. The code introduced several numerical enhancements not present in earlier versions (Chervin and Semtner, 1988).

At the present time the fastest computing machines available are still not capable of integrating a global eddy resolving model from an isothermal state of rest to statistical equilibrium (under annual mean forcing) without considerable assistance in the spin-up phase, even in the highly optimised form of SC88. A completely prognostic primitive equation eddy-resolving ocean model, spun up with seasonal wind and thermohaline forcing appears to be several years away. The strategy employed in SC88 is similar to that of CME and FRAM, except that the grid is fixed through all phases of the integration. The first 4 years of integration relax the global ocean temperature and salinity toward Levitus' (1982) annual mean fields (restoring time 1 year), while at the same time gradually introducing Hellerman and Rosenstein (1983) wind forcing. Laplacian horizontal mixing is used for both the momentum and thermohaline components. The relaxation time scale is then reduced to three years for the next 6 years of integration, and then removed altogether for the upper ocean (except at the surface) for a further 10 years of integration. At this point the upper ocean is supposed to have freely adjusted on decadal time scales (the thermocline circulation in the parlance of this paper), but the deep ocean is still tied to climatology. Finally, in consideration of the genesis of an eddy field, the Laplacian friction is replaced by a scale-selective biharmonic form which allows the eddy field to reach realistic energy levels (Semtner and Mintz, 1987). This configuration is integrated from year 18 of the non-eddy field run until a quasi-statistical equilibrium has been achieved. Like the CME and FRAM projects, SC88 required considerable human and machine resources and broke new ground in the numerical methodology and in the analysis and presentation of results. The primary fields together with relevant statistics are archived every 3 days. The saving and retrieval of such large quantities of data poses its own particular problems, a consideration which should not be overlooked in the design of an OOS.

SC88 successfully provided a global map of the mean and eddy circulations which is in broad agreement with existing observations (e.g. altimeter data, Cheney et al., 1983). The model provided snapshots of the variability within a suite of western boundary current regimes, providing unprecedented scope for detailed study of the interconnectivity of the western boundary current regimes. The most interesting result was the apparent confirmation of the role played by the Indian Ocean as a conduit for water travelling between the Pacific and Atlantic Oceans. Semtner and Chervin (1990) also used the model to study the possible effects of mesoscale and seasonal variability on acoustic travel times in the Munk and Forbes (1989) proposed acoustic technique for measuring global ocean warming. Their results suggested the warming signal could be delineated from the noise of such variability. The scope for studying patterns of variability, from short through basin to global scales (e.g. inter-basin gyre connectivity and cross equatorial flow), provides both challenge and encouragement in the design of an OOS. Semtner (1989) mentioned some of the aspects which are currently under investigation, and anticipates that a global 1/6 degree 40-level ocean model might be feasible toward the end of WOCE.

(d) A model for global water mass formation

Cox (1989) concentrated on a different aspect of the global ocean circulation - the processes by which the major water masses of the World Ocean are formed. The Cox (1984) model is employed once again, but with an idealised representation of the major ocean basins and topographic features. As such the experiments were not simulations of the World Ocean circulation, but served as a laboratory for testing the importance of different elements of the system, namely the presence of a circumpolar current in the Southern Ocean, the influence of wind-driving versus thermohaline driving, and the influence of a source of salty (Mediterranean) water in the North Atlantic. Cox also introduced a novel method for determining mixing ratios (of different water masses) in the model ocean via the introduction of multiple passive tracers.

The results showed that a thermohaline driven circulation without a circumpolar current or North Atlantic Deep Water source could only capture the coarsest aspects of the observed temperature and salinity patterns. Subantarctic water dominated the water mass structure of the world ocean. The opening of Drake Passage and subsequent generation of a circumpolar current changed the meridional flow in a fundamental way, isolating the waters formed south of the current from the rest of the domain, and permitting waters of mid-latitude and northern origins to occupy a greater proportion of the domain. Wind-forcing increased the strength of the circumpolar flow and further isolated the subantarctic waters. The simulated northward penetration of (intermediate) waters from north of the circumpolar region and southward from the North Atlantic and Pacific was also improved. Finally the addition of an upper ocean source of salty water in the eastern North Atlantic substantially improved the deep saline structure of all basins, and produced an overall improvement in the salinity structure.

This study demonstrated that current models, even in the absence of mesoscale eddies, can capture several of the key water mass formation processes of the world ocean and that the simulated distribution of these masses is consistent with observations. The presence or not of sources for particular water types (and their relative buoyancies) are crucial in determining the ultimate level to which these waters circulate and the relative preponderance of the different masses. Bryan (1991) has showed that for meridional transport of heat the model resolution is not of paramount importance. The implication is that models with resolutions similar to Cox (1989) do give meaningful results on water mass formation which may hold for finer resolution and, hence, are relevant for designing observing systems which hope to capture such aspects.

(e) Alternate OGCM configurations

The initiatives discussed above all derived from the GFDL model, although each included enhancements and modifications to both the physics and numerical design. However it is desirable to maintain a variety in the approach to any modelling problem, no matter how well credentialled a particular model may be. Two of these alternate approaches are mentioned here to demonstrate the possible benefits of diversity for OOS.

Hasselmann (1982) proposed that the conventional primitive equation model could be made more efficient by filtering out faster moving gravity waves using the quasi-geostrophic approximation. The circulation is divided into a barotropic component with associated surface displacement, and a baroclinic component which includes prognostic equations for temperature, salinity and other tracer fields of interest. On the time scales of ocean climate the flow is in approximate geostrophic balance and the depth-averaged flow responds near-instantaneously to surface stress and thermodynamic forcing. The model is closed through the addition of frictional layers at solid boundaries and at the equator (additional terms are required in the vicinity of the equator). Additional detail is given in Maier-Reimer et al. (1982). The model has been employed in a variety of climate-related situations (e.g. Maier-Reimer and Hasselmann, 1987; Cubasch, 1989).

Haidvogel et al. (1990) (see also Haidvogel, 1990) proposed a semi-spectral primitive equation ocean circulation model. The equations of motion are the hydrostatic primitive equations, much as in the GFDL model, with an explicit Price et al. (1986) style mixed layer at the surface and options for periodic or closed boundaries, as well as various forms of frictional dissipation. Of particular interest are the application of a bathymetry-following (sigma) coordinate system in the vertical, and a horizontal orthogonal curvilinear coordinate system for improved handling of lateral boundaries. The vertical dependence of the variables are expressed in terms of a continuously varying set of orthogonal structure functions (Chebyshev polynomials) which offer better resolution near the top and bottom surfaces and improved accuracy. This resolution may not always be placed to best advantage, for example, when dealing with subsurface jets. Haidvogel (1990) discussed a variety of applications. To date, the model has not been applied in global or basin scale ocean climate studies but this should be feasible. The improved accuracy and efficiency of the Haidvogel et al. (1990) semi-spectral model offers a viable alternative for situations where the resolution of vertical mixing and advection is of paramount importance.

6.1.4 OGCMs in a coupled model environment

The state of coupled climate modelling has been the subject of several reviews (e.g. Schlesinger and Mitchell, 1987, Meehl, 1990) and was a principal concern of the recent IPCC scientific assessment of climate change (e.g. Cubasch and Cess, 1990 and Bretherton et al., 1990). The principal concern here is an assessment of the current state-of-the-art systems with respect to simulations of the deep ocean circulation. The first coupled experiments for doubled carbon dioxide scenarios employed slab or mixed layer oceans (see Cubasch and Cess, 1990). Bryan et al. (1988) were the first to suggest that such models may not be capturing key interactions between the upper and deep ocean, principally the formation of deep and intermediate waters and the consequent transport of heat and salt. The obvious solution was to incorporate an OGCM, but resources were to provide a tight constraint on such remedies.

In contrast to the pioneering study of Bryan et al. (1975), where the aim was a realistic simulation of present climatic conditions, most modern coupled model studies have been concerned with issues of climate change; the lack of realism in the control simulation was only important in so far as it contributed to the uncertainty of the predictions. It soon became apparent that deficiencies in the oceanic and atmospheric components had an immediate impact on the way such integrations reached equilibrium. The separate components differed in their simulations of the surface heat and freshwater fluxes, and in turn differed from the "best" observed estimates, so that the coupled system tended toward an unrealistic climate. The usual solution (if indeed a solution is needed; Meehl, 1990) was to adjust the surface exchanges to account for this mismatch, usually referred to as "flux correction" (Sausen et al., 1988) or "flux adjustment" (Manabe and Stouffer, 1988). The root cause of the ocean model - atmosphere model mismatch remains unclear, but the likely candidates on the oceanic side are poor resolution, uncertainty in eddy parameterizations, poor upper ocean physics, and poor representation of the deep thermohaline field (i.e. the deep recirculation of heat, salt, etc.).

The OGCMs employed in coupled climate studies are generally similar to those which were being used in the late 1970's and early 80's for ocean-alone simulations (e.g. Han, 1984; Meehl et al., 1982; Bryan et al., 1975; Bryan and Lewis, 1979). Running in coupled mode (particularly in synchronous mode) is extremely demanding in terms of resources, the major impositions being restricted horizontal and vertical resolution and limited range of integrations (equilibrium may not always be reached, e.g. Schlesinger and Jiang, 1988, and important seasonal effects must be excluded, e.g. Bryan et al., 1988). Horizontal resolution is typically around 4° and the number of vertical levels ranges from the bare minimum of two (Gates and Potter, 1990), through coarse resolution (four as in Washington and Meehl, 1989) to intermediate resolution (twelve as in Manabe et al., 1990). We will assume the latter two studies are representative of OGCMs currently incorporated in coupled simulations, and use the zonally averaged oceanic temperature and salinity structures from these studies as a guide to the performance.

SSTs are typically too cool in low latitudes and too warm in high latitudes. The former deficiency is partly attributable, either directly or indirectly, to the coarse horizontal and vertical resolution whereby the unique meridional structure of the equatorial zone (e.g. the equatorial wave guide and eastern basin upwelling) is only partially represented. The crude representation of vertical eddy mixing is also a factor. This is consistent with the relative performance of the Washington and Meehl (1989) (their Fig. 10) and Manabe et al. (1990) (their Fig. 3) models. The relatively warm high latitude SSTs can be traced to exaggerated transport of surface heat, particularly in high southern latitudes, and the crude representation of the seasonally varying thermohaline circulation. The vertical distribution of temperature is usually characterised by a thermocline which is both too deep and broad (as in ocean-only models), and by a deep ocean that is far too warm. Manabe et al. (1990) reported deep equilibrium temperatures of 4°C which they attributed to lack of wintertime salinity-forced deep convection in their model (see also England, 1992). Washington and Meehl (1989) reported much better correspondence with observed fields (their Fig. 12), but this may be due in part to their initialisation and integration strategy (e.g., the <2°C water in their computed fields does not appear to be ventilated at high latitudes thus suggesting it may be left over from the initial state). The adequacy of the salinity simulations is difficult to gauge due to the influence of surface water flux adjustment (Manabe et al., 1990) and initial conditions (Washington and Meehl, 1989). Both simulations capture some of the observed structure, e.g. the Arctic halocline and the subtropical surface maxima, but fail to capture more subtle features such as the salinity minimum signature of Antarctic Intermediate Water and the deep penetration of salty water near 40°N. The root cause of these deficiencies is not immediately clear but poor physics and poor resolution, along with the lack of a seasonal cycle, appear prime candidates. The report of the first session of the WCRP Steering Group on Global Climate Modelling (WCRP, 1991b) discussed the present state of coupled modelling and issues which should be addressed.

The degradation of surface fields in coupled models is significant and, not surprisingly in view of the deterministic nature of the oceanic component, does lead to abnormal excursions in the equilibrium climate. For the time being "flux correction" techniques are the only recourse for climate sensitivity experiments where the equilibrium climatic state is required to be in reasonable accord with observations. For global climate modelling it is clearly important to correctly simulate the ventilation of the sub-tropical gyres and the deep circulation of the sub-polar gyres. These processes, along with heat transport by the boundary currents and unresolved deep topographic transports are the key to realistic coupled climate model simulations. One encouraging aspect of the model results published thus far is the apparent natural formation of variability at interannual and decadal time scales. On the debit side, the treatment of cryospheric interactions in coupled models appears far from satisfactory (WCRP, 1991b), and the oceanic seasonal cycle is yet to be captured within any skill.

6.1.5 Modelling the transport and storage of tracers

The aim here is to present a brief overview of ocean modelling in the context of deep circulation of geochemical tracers. The present discussion focuses on the global transport of ocean constituents through the combined effect of upper ocean (mixing) and deep ocean (advective, convective) processes. Sarmiento and Toggweiler (1984a,b) pointed out that 75% of the ocean volume, principally those waters of the cold water sphere, are ventilated through about 4% of the ocean surface, mainly at high latitudes. It is this renewal of the deep water sphere at times scales of the order 1000 years that is the principal focus of large-scale tracer models.

There are basically two approaches to the prognostic problem (note that inverse theory is also widely used in this context). One is to treat the ocean as a collection of boxes, as in Sarmiento and Toggweiler (1984a,b) and Broecker and Peng (1986, 1987), with the exchange between boxes being determined by prescribed diffusion and advection rates. The other is to treat carbon dioxide, tritium and other non-reactive constituents as passive tracers and adopt a prognostic dynamic ocean model (e.g. Holland, 1971; Bryan and Lewis, 1979), coupled with an air-sea exchange model, to determine the advection, diffusion and convection rates.

Sarmiento and Bryan (1982) and Sarmiento (1983) performed a bomb-tritium simulation in the North Atlantic using the GFDL OGCM. Seasonal convection was found to be as important as downward advection and diffusion in determining tracer penetration. Indeed the effective "diffusion" of the model is dominated by advective and convective contributions rather than the prescribed vertical tracer diffusion. Such a complex behaviour cannot easily be captured in simpler box models with prescribed vertical mixing rates and no thermodynamic circulation (e.g. Oescheger et al., 1975). Sarmiento and Toggweiler (1984b) pointed out that if the box-model approach is to work for the deep ocean then it is essential that the deep water be ventilated appropriately through a high latitude box, thus making it possible to form deep water with the appropriate characteristics. The implications for the carbon cycle are that an increase in high latitude carbon productivity coupled with a reduced thermohaline overturning could lead to significant changes in atmospheric CO_2 concentrations, such as occurred between the last glacial and interglacial periods.

Bryan and Sarmiento (1985) made a similar point based on perturbations to the surface temperature and passive tracer forcing of OGCMs. They note that the effective vertical penetration of surface tracer or heat perturbations is over five times that by prescribed vertical diffusion. This is due to the effect of deep convection at high latitudes, the implication being that vertical mixing rates can be quite high over localised regions, and that any change in the high latitude overturning rate will have a substantial effect on the net downward diffusion of tracers.

A related issue is the possibility of positive and negative feedbacks in deep water recirculation. Bryan and Sarmiento (1985) argue that warm anomalies at the surface would suppress high-latitude convection and reduce ocean ventilation (cooling in the case of the ocean), and thus reduce the net heating of the atmosphere. This was a key element of the Manabe et al. (1990) and Manabe et al. (1991) coupled studies. A similar sensitivity to climate change is at the heart of the suggestions by Broecker et al. (1985), Broecker and Denton (1990) and Manabe and Stouffer (1988), among others. Increased fluxes of freshwater into the surface water of the North Atlantic (from melting glaciers or reduced evaporation/increased precipitation) would reduce the surface salinity and suppress deep mixing, while at the same time reducing the upper ocean northward flux of warm water; The continents adjacent to the far Northern Atlantic would be chilled while mid-latitudes would get warmer.

Maier-Reimer and Hasselmann (1987) modelled the levels of inorganic carbon in the ocean as a passive tracer advected by the ocean circulation. The model carbon cycle is closed at the surface by a one-layer diffusive (motionless) atmosphere which is interfaced to the ocean using a standard CO_2 flux relation and a chemically active mixed layer. This model excludes biological sources and sinks. The model reproduces the broad pattern of CO_2 distribution in the ocean but, due to the absence of a biological pump, the surface pCO_2 may be underestimated in upwelling regions by about a factor of 1.5 (e.g., compared with Bacastow and Maier-Reimer, 1991). Comparisons with other models suggested the response function for CO_2 impulses could be captured with relatively simple box models. They also suggested that determination of future CO_2 concentrations would depend on estimations of the detailed time history of the oceanic CO_2 uptake since this effects the ability of the ocean to sequester CO_2 in the deep.

Toggweiler et al. (1989a,b) discussed simulations of radiocarbon distribution in a coarse-resolution world ocean model (similar to the Manabe and Stouffer, 1988 model). Toggweiler et al. (1989a,b) recognised the deficiencies of such models and the adverse effects they might have on inferences drawn from the model. The five experiments examined robust diagnostic methods (e.g. Sarmiento and Bryan, 1982) versus purely prognostic simulations, and the effect of various surface gas exchange coefficients. Biological production was ignored. Toggweiler et al. (1989a) examined the steady state (order 2000 years of integration) pre-bomb distributions. The model reproduced the mid-depth ^{14}C minimum observed in the North Pacific and the strong front at 45°S. In the Atlantic penetration of relatively old water from the Antarctic produces an unrealistic layering of the distribution. Spatial variation in the surface gas exchange rates did not influence the deepwater radiocarbon values. Ventilation in the circumpolar region is controlled by the "Deacon cell" of the model (the lack of such a cell in the North Pacific and Indian basins restricted the ventilation there). They found a fully prognostic model gave better simulations than semi-diagnostic models in spite of the clearly poorer interior temperature and salinity simulation, principally because the observations prevented significant overturning and deep ventilation.

In Toggweiler et al. (1989b) a pulse of ^{14}C is added to the atmosphere, using Toggweiler et al. (1989a) as the initial condition, and used to follow the post-bomb ^{14}C distributions. The model successfully reproduced the GEOSECS inventories (Broecker et al., 1985), but predicted a significantly different pattern of ^{14}C uptake in the decade after GEOSECS. The post-GEOSECS buildup is confined to the sub-thermocline layers of the North Atlantic and the lower thermocline of the South Atlantic, and to 2000m and above in the circumpolar region. Subantarctic Mode Water formation is a key process in carrying ^{14}C into the thermoclines of the southern hemisphere, but the model has a restricted domain for mode water formation and so fails to ventilate in the appropriate regions. The movement of bomb ^{14}C into the deep circumpolar waters and the deep North Atlantic is too slow. Sarmiento et al. (1991) have argued that tracers provide an important independent validation of the water mass and transport realisations from OGCMs and are useful for isolating weaknesses in the model formulation. For example, in the Sarmiento et al. (1991) model the bomb-produced radiocarbon inventory is too low compared to observations, so they inferred their estimate of the oceanic uptake of carbon was probably a lower limit to the true value.

6.1.6 Two- and three-dimensional physical-biological models

The chemical models discussed above do include some biological processes but usually in a simplistic form. Multidisciplinary programs such as JGOFS have spurred the development and testing of spatial models with both physical and complex biological systems. Fasham et al. (1990) coupled the OGCM used by Sarmiento et al. (1988) with a 7-compartment biological model. This general plankton food web model has been used to investigate a variety of biogeochemical processes in the upper ocean (Toggweiler, 1990). These models are extremely demanding of resources particularly if the biological component is to be kept realistic. Realistic simulation of general production and vertical nutrient flux would also require eddy-resolving physical scales, an unrealistic demand given the present resources.

In the absence of the resources required to run global-scale physical-biological models, regional models have appeared, spurred by availability of biological information from remote sensing platforms. For example, Walsh et al. (1988, 1989) developed models for the Middle Atlantic Bight and Gulf of Mexico, respectively, while the southeastern US continental shelf has been modelled by Hoffman (1988) and Ishizaka (1990a,b,c). Specialised basin-scale models have also been developed for several regions including the North Atlantic (Wroblewski et al., 1988; Wroblewski, 1989). The physical models are generally eddy resolving but the interface between the physics and biology varies (e.g., no horizontal advection, diffusion or no vertical advection). The biological models tend to be somewhat simpler than that employed by Fasham et al. (1990) (e.g., 1-3 compartments), focusing on the primary producers and the nitrogen pools, with simple closures for losses to respiration, grazing and sinking.

Ocean-margin coupling is important since the continental shelves act as a buffer zone for the biogeochemistry of the ocean interior. Regional models for these zones are in an advanced stage of development but require improved knowledge of the forcing and better validation data sets. In the context of using physical-biological models within an OOS it is important to remember that parameterizations developed for a particular location or scale may not be transferable to other regions. The problem of scaling-up knowledge from the small scales to the large scales of an OOS is a particularly difficult problem. It is important that the *in situ* observations be gathered to enable such model developments to take place. The 10-year JGOFS time series is unlikely to be capable of assessing the absolute accuracy of biological models given that biological communities can vary over decadal time scales and that the signal-to-noise ratio of such fields is likely to be small. The processes being considered are extremely complex and not well understood, suggesting that for the near-term, the OOS will need to concentrate on simulation and validation aspects rather than assimilation.

6.2 Assimilation and prediction: Inverse modelling

The prognostic models discussed above are not well suited for systematic testing of model parameters, model forcing, or for assessing compatibility with observations. In a sense the models have used only part of the information available, namely deterministic equations for the circulation and some estimate of the external forcing of the system. No allowance has been made for errors in these components, and the vast information available from observations has not been used explicitly. A better strategy might be to combine this prognostic skill with data to produce optimal estimates of the oceanic state, together with estimates of the uncertainty in the product and in the constituent parameterizations. For the deep (or global-scale) ocean these techniques are usually referred to as inverse methods, but they are closely related to the variational and control techniques discussed previously under the heading of "data assimilation" (Wunsch, 1989a,b; Ghil and Malanotte-Rizzoli, 1991). In either case the focus is on combining data with models and, for the global deep water sphere, this is a special and subtle problem. The various approaches have been discussed in Anderson and Willebrand (1989), and have been the subject of several recent workshops (e.g. "Inversion of Ocean General Circulation Models", WCRP, 1989d; "Assimilation of Observations in Meteorology and Oceanography", WMO, 1990). Wunsch (1989b) gave a particularly clear account of the inverse approach and the reader is referred there for details and an extensive reference list. The advent of WOCE and advances in computer resources have given added impetus to the application of such techniques to global hydrographic and geochemical data sets. It is perhaps in this latter aspect, the use of non-hydrographic data, that sets the applications discussed here apart from those previously discussed in tropical ocean and mesoscale ocean "weather" prediction. Tracer data provide additional, potentially powerful constraints on the inferred circulations.

One approach to the problem might be to adapt the existing and new techniques of seasonal and ocean weather prediction. Sequential data assimilation, as practiced in NWP and lately in NOP, would not seem to be viable for the large space and time scales of the deep ocean - even if WOCE were successful on all accounts it would hardly provide sufficient data to initialise a model, let alone provide the time-space history needed for a synoptic analysis and sequential assimilation. However, if the questions being asked were modified, say to concentrate on the annual cycle, then some of the methods might become feasible. Thacker et al. (1989) developed an adjoint model for the GFDL OGCM which closely followed the computational strategy of the forward model. While some aspects of the physics, particularly those which include non-linear time-dependent logic (e.g., to convectively adjust or not), do pose significant problems, this approach appears to offer considerable scope for studying the sensitivity of ocean climate models. The practical application of the adjoint method to real global-scale problems has yet to be tested.

Inverse methods grew out of the inadequacies of the dynamic method for determining ocean circulation (Worthington, 1976; Wunsch, 1989b). The velocity shear could be determined from hydrographic data and an equation of state but the method did not ensure consistency in space or with the distribution of non-hydrographic data, and relied on a poorly known level of no motion for determining the absolute velocity. Inverse methods sought to remove these inconsistencies by requiring the circulation to simultaneously satisfy a variety of constraints and observed distributions. The vast majority of inverse models have been applied to the problem of determining the mean (steady-state, equilibrium) circulation of the oceans consistent with, but not necessarily exactly fitting, various dynamical and conserving principles and observed data. Just as in most prognostic OGCMs, some important temporal and spatial variability must be represented by appropriate parameterizations until resources are sufficient for explicit resolution. The dependency on horizontal parameterisations will presumably diminish as resolution is improved but the same may not be true of vertical eddy parameterisations. The power of inverse models is in their ability to systematically incorporate information from disparate sources, either in the form of observations or relational equations, and provide an estimate not only of the oceanic state (as represented by the constituent fields) and associated errors, but also of the various model parameters (e.g. mixing coefficients).

The beta spiral method (Schott and Stommel, 1978) required the motion to be geostrophic and for the potential vorticity to be locally balanced. When this relation is combined with the thermal wind equations and conservation of potential density we get a relationship between the spiralling of the lateral velocity vector with depth and the vertical velocity. By applying this equation at many levels we get a formally over-determined inverse system of equations for the unknowns, lateral and vertical velocity at the reference level. A variety of methods are available to solve the system including singular value decomposition. Olbers (1989a,b) and Wunsch (1989b) discussed some of the issues involved.

Schott and Stommel (1978), Olbers and Wenzel (1989) and Killworth and Bigg (1988) demonstrated the usefulness of the beta spiral method. Olbers et al. (1985) applied the method to North Atlantic data and, in addition to the determination of the absolute flow field, showed that the method could be used to infer diffusion rates. The method appeared to work well in areas where diffusion was a dominant process in the tracer balance, but the results were less compelling where this was not the case (e.g. mid-gyre in the North Atlantic). Noise in the data may be a problem. It is also not clear how much the pre-processing of data (e.g. to achieve gridded values) affected the determinations of diffusion rates - excessive smoothing may indirectly lead to spurious diffusion rates. The problem of noise may also be dependent on the details of the actual implementation, for example the use of tight and loose constraints within the implementation. Olbers (1989b) and Olbers and Wenzel (1989) presented similar calculations for the Southern Ocean and these estimates seemed consistent with our knowledge of mixing in this region (large values near the strong circumpolar current). The results were also consistent with the few observations available (from buoys and altimeter data) but it was difficult to quantify the accuracy of the estimates without prior knowledge of the variance in the ingested hydrographic data.

As Olbers (1989a,b), Olbers and Wenzel (1989) and McDougall (1988) point out, there are several aspects which require careful attention. The fact that the method is applied *locally* means that conservation of mass is not assured. This can be rectified by seeking a velocity field which is close to the beta-spiral inverse field but non-divergent, and that takes account of Ekman pumping at the surface and solid-boundary conditions. For the North Atlantic this generally results in a smoother field (Olbers and Wenzel, 1989). The successful implementation of the method also (naturally) requires that the lateral velocity vector veer with depth. If it does not, then the inverse problem may approach ill-posedness, as manifested by extremely low values of the matrix condition value (Olbers et al., 1985). A related problem occurs in the Antarctic Circumpolar Current where the zonal velocity varies little with depth. The eigenvalue associated with the zonal flow is relatively small thus making the determination of the reference zonal velocity sensitive to error. This can be overcome by including further conditions on the flow, such as steering by bottom topography (Olbers, 1989a,b). McDougall (1988) showed that the beta-spiral method is best written for neutral surfaces rather than isopycnal surfaces. Conservation of tracers such as isopycnal potential vorticity is achieved naturally on neutral surfaces. Olbers (1989a) examined the determination of the diffusion tensor for cartesian, isopycnal and neutral surfaces and could not clearly identify a superior orientation of the tensor. The fact that these issues have a large bearing on the information derived from the method suggests they might well be important for the development of a OOS.

Inverse box models have now been applied in a wide variety of problems (Wunsch, 1977, 1978; Roemmich, 1980; Pollard, 1983; Fu, 1981, 1986; Wunsch, Hu and Grant, 1983; Rintoul, 1988; Schlitzer, 1987, 1988; Bolin et al., 1987). The use of such techniques is largely superseding and supplanting the use of traditional dynamic methods. It is sensible that diagnosis of the flow field should not simply be a function of the hydrographic data, but should use as much model and other dynamic and tracer data as is available. The problem then becomes one of fixing the (relative) accuracy of these measurements, choosing the appropriate dynamical and tracer constraints (e.g. geostrophy, Ekman dynamics, conservation, diffusion), and determining internal and external sources and sinks (e.g. wind forcing, biological productivity/consumption). The aims include determination of the absolute velocity field, the various property budgets, and determination of mixing coefficients. The inverse method provides estimates of solution variance and resolution for testing against *a priori* assumptions, and an ability to incorporate acquired knowledge of the fields (mainly statistical; Wunsch, 1989b). The temperature and salinity data are the dominant determinants for the velocity field (through geostrophy) but some recent experiments with non-linear inversion methods (Mercier et al., 1989; Mercier, 1989) have shown that the density field can also be corrected using direct measurements.

Nutrients, oxygen, tritium and radiocarbon have all been used in inversion studies, the relative usefulness of the data base components usually being determined by the adequacy of knowledge of the measurement errors (e.g. instrument and sampling problems) and of the sources and sinks for the various components. Nutrient data have proven useful in constraining (lowering the estimated error of) the circulation and the diapycnal mixing rates (e.g. Rintoul, 1988, 1989). The fact that chemical data contain information independent of the physical measurements suggests the inverse determinations of the circulation from properly synthesised chemical and physical data should be superior. The use of transient tracers for determining ocean transport is a more difficult problem. Wunsch (1984) showed that the equatorial upwelling in the Atlantic could be determined (constrained) by radiocarbon data. Wunsch (1987) discussed the regularisation problem for transient tracers. Jenkins (1989) showed that bomb-tritium data alone could only weakly constrain the circulation, but suggested that its use in combination with helium-3 data may prove more powerful. The cause of the problem here is the uncertainty in the surface forcing. Mémery and Wunsch (1990) tested the feasibility of constraining ocean models with transient tracer data. They found that existing tritium observations would only weakly constrain the interior ocean circulation even if it were assumed that atmospheric transfer rates and open boundary conditions were known with reasonable accuracy. Nevertheless they conclude that, with the appropriate tracer and good knowledge of the tracer input function (use a closed domain with good surface information), such techniques should yield useful information on the circulation.

WCRP (1989d) discussed at some length the issues facing inverse theory practitioners, and these issues are also relevant here. The great advantage of inverse theory, as against traditional methods of analysis (e.g. Gordon et al., 1982; Levitus, 1982), is that an estimate of the error in the diagnosed field arises naturally out of the methodology. True, this estimate of the error is dependent on reliable estimation of the variance in the field and knowledge of the spatial and temporal variability. The estimates of the state must be representative of the true equilibrium state of the field (errors of representativeness have been discussed at length in NWP, e.g. Lorenc, 1986). Wunsch (1989b) made a strong case for pursuing inverse and other estimation methods beyond estimation of the field, to look at the soundness of *a priori* assumptions through calculation of estimated field variances and covariances.

The identification of systematic errors, due to forcing error or model deficiencies, is also an important issue. WCRP (1989d) discussed the format of data being used for inversion, weighing the use of raw data against already gridded products (the analogous issue in NWP is the use of super-observations to represent several individual pieces of information). For practical reasons gridded data were preferred but the problems with pre-processing, especially smoothing (Olbers, 1989b; Rintoul, 1989) were important. A related problem is that of estimating solution variance which, for the under-determined problem (no redundancy in the data), usually requires a reduction in the effective degrees of freedom through smoothing. Such estimates need to evaluated on many realisations of the same situation.

For both the practitioners and end users of inverse theory applications the sensitivity of the solutions to the minimisation criterion is an important issue. The essence of the under-determined inverse problem is that additional information is needed to close the problem and this information usually takes the form of a minimisation (say diffusion) or smoothness criterion. Ideally this criterion should have a sound physical basis. The inverse model circulation and estimated error characteristics, and comparisons with independent data, ultimately attest to the appropriateness of the *a priori* assumptions.

Wunsch (1989a) suggested that the inverse modelling community might (should) adopt a similar strategy to the Community Modelling Effort and develop a comprehensive model (the North Atlantic was the obvious domain), using state-of-the-art computing and numerical techniques to reduce the box size and enable consideration of many different fields and constraints. Wunsch suggested that a global one degree square, ten level model is feasible, so long as a community-based modelling approach was adopted. Even for the steady model this would require considerable effort to prepare the data (with error estimates), configure the domain and model, and decide on the best solution approach. The WCRP (1989d) workshop recognised the value of a variety of approaches to the inversion of oceanic models, and that work should now begin on developing suitable time-varying inverse models.

6.3 OOS network design and quality control for the deep ocean

Quality control of deep ocean data is a difficult problem, and is usually accomplished through a mix of subjective and simple objective methods. The cost of gathering deep ocean data makes it crucial that its integrity be assured and that little data is wasted. On the other hand the data base for the deep ocean is sparse in time and space and, since quality control inevitably depends upon previous information, will always operate under extremely difficult circumstances. The accuracy of global-scale ocean models is such that they cannot yet be used to guide quality control of data; However inverse models inevitably incorporate a form of quality control within their formulation since they are in essence a data-fitting model - bad data will fit poorly. We are not aware of any published accounts of the use of inverse models for detecting errors in deep ocean data.

Models have been used at various stages in the design of ocean observing networks for the deep ocean. Bretherton et al. (1976) were among the first to look at the oceanographic experiment design problem. Their task was to design a current meter array that would give the best possible map of the mesoscale eddy structure, as part of the Mid-Ocean Dynamics Experiment. Their approach drew on experience in NWP where, with information on the noise and signal levels of the observations (and their spatial coherence), an estimate of the expected error in the mapped field could be obtained, subject to the specification of an objective function (e.g. least rms error in the mapped field). While this approach has proved extremely useful in many different contexts (e.g. Meyers et al., 1991), it remains sensitive to the particular statistical assumptions being used, and is not easy to use to "predict" the best array. Bretherton and McWilliams (1980) did approach the problem from this perspective, using a slightly more general statistical and information theory.

The key to such applications is often in the choice of the objective function. Bennett (1985) chose an objective function to characterise acoustic tomography arrays (Barth and Wunsch, 1990 used a similar function). Bennett (1985) assessed the ability of a set of arrays to map a continuous (synthetic) field using inverse techniques. Barth and Wunsch (1990) discussed a similar problem, but carried out the optimisation of the objective function by simulated annealing. They concluded that such techniques, when carefully applied, would give results superior to those of traditional methods of array design.

OSSE/OSE-type experiments are often carried out within the context of inverse modelling. For example, comparing the circulation obtained with hydrographic data alone compared with that obtained by including chemical tracers. The problem is, however, in the validation of the experiments. In NWP, and in prognostic modelling in general, validation of the improved/decreased skill of the model is ascertained by comparison of forecasts and analyses (i.e. comparison against independent data). The very nature of the inverse methodology ensures that additional information, so long as it is not biased or systematically in error, will lower the expected error of the ocean state simulation. It is often more difficult to judge whether a particular system makes a <u>significant</u> impact on the estimation of, say, the lateral velocity field. As Olbers (1989b) pointed out in his inversion study of the Southern Ocean, it is almost impossible to quantify the accuracy of estimates for, say, diffusion since little independent evidence exits. One approach, as in Killworth and Bigg (1988) is to use synthetic data generated from OGCMs. However, as borne out by the experiences of FGGE, results from simulated observations do not always translate over to real data systems. Nevertheless the data generated by high-resolution modelling projects such as CME, FRAM and Semtner and Chervin (1988) do offer opportunities to test *a priori* assumptions and variance estimates on "known" fields; The reduced dependence of these models on eddy mixing parameterisations should engender greater confidence in the results of such tests.

There have been no attempts to use OGCMs directly in the design of observational networks. Certainly programs such as FRAM and the CME provide many results which may stimulate observational programs, or help define the relative roles of particular components within an observation program. But as yet resource limitations prevent the repeated experiments which would be necessary to implement true OSSE/OSEs.

6.4 Developments required for the deep ocean component of an OOS

The development of models for the deep ocean is inextricably linked to progress in each of the other components - surface forcing, mixed layer physics (for tracers and heating) and ventilation of the thermocline. We should also not overlook the tropical oceans. Research there is concentrating on seasonal and interannual variability, but it is in these regions (e.g. the western Pacific warm pool) where many of the important air-sea interactions are taking place and it may well be that these processes are critical for understanding the global circulation. The failure of coupled models with poor resolution of the equatorial regions is perhaps a forewarning of this key role. On the same theme, the equilibrium climate of the oceans may also be sensitive to the interannual reorganisation of the tropical oceans. For coupled models a severe test of their integrity will be their ability to realistically simulate interannual variability in the tropics. However the first priority must be to successfully produce the observed seasonal cycle, an ability that is presently absent from most coupled models.

The primary focus of modelling at this time is on simulations of the current climatic conditions. Computer power has now reached a stage where truly eddy-resolving models of the global ocean may be possible. Both prognostic and inverse models are being used to build a better understanding of the ocean circulation as it now. This is the primary objective of WOCE, but the design and construction of an OOS must be mindful that this building of knowledge will almost certainly continue well beyond WOCE. Models can play a critical role in determining how best to gather this information, and the modelling community should be encouraged to develop and define this strategy. In future, tried and tested strategies should be in place for evaluating the relative worth of different observing systems in the determination of the global ocean circulation.

The ultimate goal is to implement global ocean prediction systems. The confidence in such predictions will be based partly on the ability of models to reproduce features of the present circulation. Some of the most severe tests will come in biogeochemistry where models will be required to reproduce current patterns of trace gas and carbon exchange, as well as the observed biological and chemical cycles in the ocean (e.g. primary productivity). This will of course require substantial progress in our understanding of the important non-conservative processes in the ocean. While there are many who would argue that credible climate perturbation experiments can be performed on less-than-perfect equilibrium climates, there will always be just as many doubters who will be suspicious of any prediction based on poor initial conditions. This will be particularly so if we cannot quantify the uncertainties in the deterministic and observed components of the prediction system.

Finally, as an example of how we might systematically build the components of OOS, we examine an initiative within GEWEX to investigate the North Atlantic water budget (Schmitt and Bryan, 1991, unpublished manuscript). This is not intended as an endorsement of this plan over any other, but rather to illustrate a way of developing observing and modelling systems in accord for their mutual benefit. Schmitt and Bryan point out the large uncertainties in our present knowledge of the net E-P over the North Atlantic - climatological estimates differ by as much as 30 mm/month. This uncertainty means we are not even sure of the sign of the mean annual buoyancy flux. We also know, from historical and contemporary data, that the North Atlantic deep circulation can be interrupted by surface salinity anomalies (Dickson et al., 1988). We know how to run models with a variety of surface freshwater fluxes to test their sensitivity; however without suitable data we cannot be sure of the appropriateness of the model parameterizations, of the validity of the forcing functions, or whether the predictions are sensible. Schmitt and Bryan suggest, among other things, that simple water mass formation models (e.g. Huang et al., 1991) and GCMs under plausible forcings and different mixing parameterizations should be used to explore the water budget. Inversion, and other classical methods, should be applied to existing data sets to improve current estimates of the net E-P flux inter-basin water exchange, and ocean-cryosphere interactions. By developing a better understanding of one basin we can better formulate OOS design for the global ocean. The testing and development of models in such an experiment is clearly of considerable benefit.

7. References

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APPENDIX

LIST OF ACRONYMS

ACC	Antarctic Circumpolar Current
AGCM	Atmospheric General Circulation Model
ATLAS	Autonomous Temperature Line Acquisition System
AVHRR	Advanced Very High Resolution Radiometer
BMRC	Bureau of Meteorology Research Centre
CAC/NMC	Climate Analysis Center/National Meteorological Center
CCCO	Committee on Climate Changes in the Ocean
CME	Community Modelling Effort
COADS	Comprehensive ocean Atmosphere Data Set
COPS	Coastal Ocean Prediction System
CZCS	Coastal Zone Color Scanner
ECMWF	European Centre for Medium Range Weather Forecasts
ENSO	El Niño/Southern Oscillation
ERS-1	Earth Remote Sensing Satellite
FNOC	Fleet Numerical Oceanography Center
FRAM	Fine Resolution Antarctic Model
FSU	Florida State University
GCM	General Circulation Model
GCOS	Global Climate Observing System
GDAP	Global Data Assimilation Program
GEOSAT	Geodetic Satellite Mission
GEOSECS	Geochemical Oceans Sections Study
GEWEX	Global Energy and Water Cycle Experiment
GFDL	Geophysical Fluid Dynamics Laboratory
GOOS	Global Ocean Observing System
IPCC	Intergovernmental Panel on Climate Change
JGOFS	Joint Global Ocean Flux Study
JSC	Joint Scientific Committee
LODYC	Laboratoire d'Océanographie Dynamique et de Climatologie
MOM	Modular Ocean Model

NAS	National Academy of Sciences
NCAR	National Center for Atmospheric Research
NEG	Numerical Experimentation Group
NMC	National Meteorological Center
NOP	Numerical Ocean Prediction
NWP	Numerical Weather Prediction
OGCM	Ocean General Circulation Model
OOS	Ocean Observing System
OOSDP	Ocean Observing System Development Panel
ORSTOM	Office de la Recherche Scientifique et Technique Outre Mer
OSE	Observing System Experiment
OSSE	Observing System Simulation Experiment
OSU	Oregon State University
OTIS	Optimal Thermal Interpolation System
SAR	Synthetic Aperture Radar
SINEG	Sea Ice Numerical Experimentation Group
SMC	Second Moment Closure
SSS	Sea Surface Salinity
SST	Sea Surface Temperature
TAO	Tropical Atmosphere Ocean (array)
TKE	Turbulent Kinetic Energy
TOGA	Tropical Ocean and Global Atmosphere
TOGA COARE	TOGA Coupled Ocean Atmosphere Response Experiment
TRMM	Tropical Rainfall Measurement Mission
UKMO	United Kingdom Meteorological Office
VOS	Volunteer Observing Ship
XBT	eXpendable BathyThermograph
WAM	WAve Model
WCRP	World Climate Research Program
WGSIC	Working Group on Sea Ice and Climate
WOCE	World ocean Circulation Experiment

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